Historic, archived document

Do not assume content reflects current scientific knowledge, policies, or practices.

Reserve
1.96
Ad6TP

UNITED STATES DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

ASPECTS OF SEDIMENTATION IN LAKE WACO

WACO, TEXAS

BY

VICTOR H. JONES and ROSS E. ROGERS

July 1952

SCS-TP-100

U. S. DEPT. OF AGRICULTURE
NATIONAL AGRICULTURAL LIBRARY
RECEIVED
AUG 4 1972
PROCUREMENT SECTION
CURRENT SERIAL RECORDS

For Administrative Use Only

AGR-SCS-FT. WORTH, TEX. SEPTEMBER, 1952

FRONTISPIECE

View from bluff on Highway 6 looking north over South Bosque arm of Lake Waco. Water 7 feet below crest.

TABLE OF CONTENTS

Page

Introduction - 1
  General information - 1
  Objectives of this investigation - - - - - - - - - - - - - 3
Reservoir and drainage area studies - - - - - - - - - - - - 4
Acknowledgments - 4
Lake Waco Dam and Reservoir - - - - - - - - - - - - - - - - 4
  The dam - 4
  The spillway - 5
  The reservoir - 5
The drainage area - 7
  Physiography and geology - - - - - - - - - - - - - - - - - 7
  Southern Great Plains Province - - - - - - - - - - - - - - 7
  West Gulf Coastal Plain Province - - - - - - - - - - - - - 10
  Soils and erosion - 11
  Land use and conservation programs - - - - - - - - - - - - 12
Methods of survey - 12
  Original survey - 12
  Surveys of 1935 and 1936 - - - - - - - - - - - - - - - - - 14
  Resurvey of 1947 - 17
Sedimentation in the reservoir - - - - - - - - - - - - - - - 22
  Rates of sedimentation - - - - - - - - - - - - - - - - - - 22
  Character of the sediment - - - - - - - - - - - - - - - - - 24
  Distribution of the sediment - - - - - - - - - - - - - - - 27
  Future trends of sedimentation in the reservoir - - - - 34
Precipitation and runoff - - - - - - - - - - - - - - - - - - 38
  Precipitation - 38
  Total water flow - 38
  High and low flows - 38
Total sediment load in the Bosque River system - - - - - 41
  Basis for estimates - 41
  Total sediment deposits and suspended sediment - - - 42
Causes of the high rates of sedimentation - - - - - - - - 42
Water consumption from Lake Waco - - - - - - - - - - - - - 44
  Past History - 44
  Future use - 44
Effects of sedimentation on future water economy - - - 47
  Basis of analysis - 47
  Results of analysis - 49
Possible remedial measures - - - - - - - - - - - - - - - - - 51
  Maintenance of the capacity of Lake Waco - - - - - - - 51
  Development of additional water storage before 1960 - 52
  Development of other water sources - - - - - - - - - - - 53
Summary - 54

LIST OF TABLES

Table No.	- Title -	Page
1	Stratigraphic table of rock formations in the Lake Waco drainage area	9
2	Major soil groups in the Bosque River basin	11
3	Relationship of soil loss factors in the Bosque River basin to sedimentation in Lake Waco	13
4	Distribution of various types of land use in 1948 in the Bosque River basin	14
5	Capacity at contour elevations, Lake Waco	19
6	Summary of sedimentation data on Lake Waco	22,23,24
7	Data on sediment samples from Lake Waco	25
8	Distribution of storage capacity and sediment in Lake Waco	32
9	Monthly discharge of Bosque River at Lake Waco during periods of low flow	40
10	Summary of total sediment load in the Bosque River system	43
11	Water pumped to City from Lake Waco	46
12	Estimated future water use from Lake Waco	48
13	Predicted effect of sedimentation on operation of Lake Waco during a critical drouth period	50

LIST OF ILLUSTRATIONS

	Title	Page
Frontispiece	View from bluff on Highway 6 looking north over South Bosque arm of Lake Waco. Water 7 feet below crest.	
Fig. 1	Location map - Bosque River Basin, Texas	2
Fig. 2	Sediment deposit in South Bosque arm of Lake Waco below Highway 6 bridge. Water 7 feet below crest	6
Fig. 3	Sediment deposit near north shore of South Bosque arm, Lake Waco	6
Fig. 4	Generalized geologic and physiographic map - Bosque River Basin, Texas	8
Fig. 5	Wave-cut bank on gravel terrace, South Bosque arm $\frac{1}{4}$ mile above highway 6 bridge	16
Fig. 6	Gravel beach and wave-cut bank on North Bosque arm, Lake Waco	16
Fig. 7	Capacity-elevation curves of Lake Waco	20
Fig. 8	Area-elevation curves of Lake Waco	21
Fig. 9	Cumulative curves showing textures of typical sediment samples from Lake Waco - 1947 survey	26
Fig. 10	Vegetal debris in North Bosque arm of Lake Waco	28
Fig. 11	Vegetal debris and sediment bars in North Bosque arm of Lake Waco. Water level 6 feet below crest	28
Fig. 12	Representative cross-sections - Lake Waco	29
Fig. 13	Longitudinal profile of channel, North Bosque arm of Lake Waco.	30
Fig. 14	Longitudinal profile of channel, main body and South Bosque arm of Lake Waco	30
Fig. 15	Average water depths in North Bosque arm of Lake Waco	31
Fig. 16	Average water depths in main body and South Bosque arm of Lake Waco	31

LIST OF ILLUSTRATIONS (Cont'd.)

Title

Page

Fig. 17 Comparison of original capacity lost by segments in Lake Waco - - - - - - - - - - - - - - - - 33

Fig. 18 Vertical distribution of sediment in Lake Waco - - 35

Fig. 19 Comparison of sediment volumes within contour intervals in Lake Waco - - - - - - - - - - 36

Fig. 20 Comparison of high flows on the North Bosque River - - - - - - - - - - - - - - - - - 39

Fig. 21 Monthly and annual water use from Lake Waco - - 45

Fig. 22 Map of Lake Waco showing ranges and original (1930) topography

Fig. 23 Map of Lake Waco showing ranges and 1936 topography

Fig. 24 Map of Lake Waco showing ranges and 1947 topography

INTRODUCTION

General Information

Waco is located on the Brazos River near the center of McLennan County, Texas at 31° 33' north latitude and 97° 9' west longitude (figure 1). It has an average annual rainfall of 35.04 inches, an average frost-free season of about 265 days, and a mean annual temperature of approximately 68°. The surrounding area lies chiefly within the Black Prairie and Grand Prairie belts which together comprise the most productive agricultural area in Texas. Cotton production, once the overwhelmingly predominant agricultural enterprise of the area, has been somewhat reduced in favor of a more diversified and better balanced agriculture. Waco is located on the main north-south highways and railroads connecting Dallas and Fort Worth and the north Texas region with Austin, San Antonio, and the Gulf Coast.

Thus situated, the city of Waco is the marketing and distribution center for a large and productive agricultural area; it is a natural site for industries related to the local products; and the topography, climate and resources are favorable to growth of a large metropolitan center.

Census records show that the population of Waco increased from 15,000 in 1890 to 27,000 in 1910, to 53,000 in 1930, 56,000 in 1940, and 84,300 in 1950. The population of the metropolitan area, including suburbs, on January 1, 1948 was estimated at 100,000 by Chamber of Commerce and Water Department officials. The more rapid growth since 1940 has been due partly to the establishment of new industries such as the enlarged Texas Textile Mill, the General Tire and Rubber Company Plant, the Owens-Illinois Glass Plant, and the large Veterans Hospital.

The first municipal water supply for Waco was provided by two private companies formed in 1872 and 1899 respectively. The facilities of the two companies were consolidated under city ownership in 1904. Until 1930, when Lake Waco was built, the system depended upon two sources of supply: (1) a group of four deep wells having an average depth of 1,975 feet and producing water from the basal sands of the Trinity group, and (2) Brazos River water. The increasing water consumption, caused by rapid growth of population and industry from 1920 to 1930, resulted in substantial reduction in water levels in the wells, while the river flow during the dry seasons was scanty and highly charged with dissolved salts.

This experience has been common to a number of the larger cities of Texas such as Dallas, Fort Worth and Austin, where increasingly heavy draft caused depletion of groundwater supplies, and local stream flow was too erratic for a reliable supply. Large surface water reservoirs consequently have become increasingly important in supplying the progressively larger water requirements of most of the rapidly growing centers of population of the Southwestern Gulf Region.

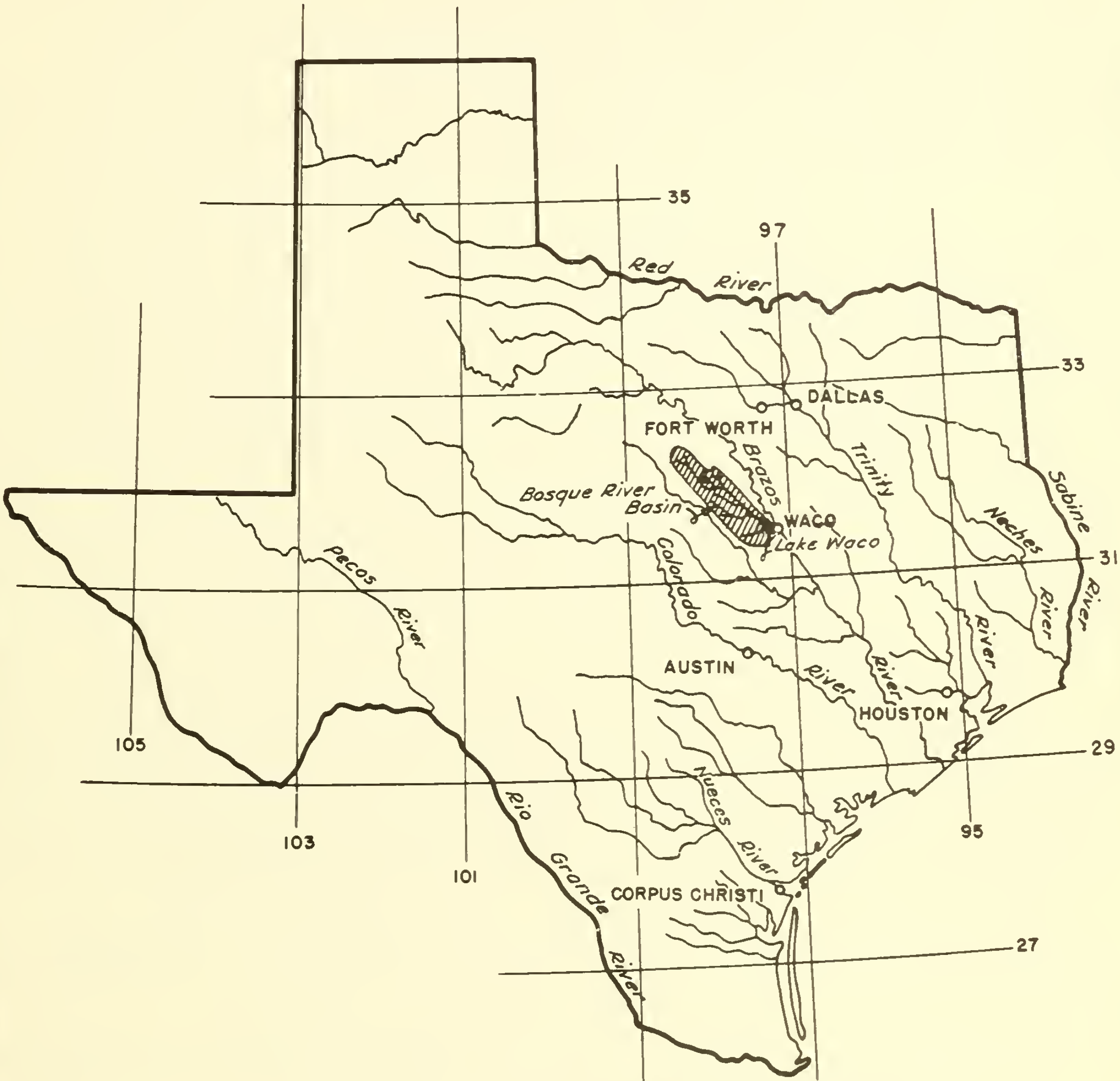


FIGURE 1
LOCATION MAP
BOSQUE RIVER BASIN
TEXAS

U. S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

REFERENCE

CARTOGRAPHIC APPROVAL TECHNICAL APPROVAL

COMPILED TRACED CHECKED DATE

10-15-48 4-L-6939

AGR-SCS-FT WORTH,TEX AUGUST,1952

When Lake Waco was built on the Bosque River in 1930, it replaced all other sources of water for the municipal system. Since the dam was completed, the rate of water consumption has increased along with the growth of population and industry. The amount of filtered water pumped annually by the city filter plant has increased from 1,469,000,000 gallons in 1931, to 1,712,000,000 gallons in 1936, to 2,447,000,000 gallons in 1944, and nearly 3 billion gallons in 1950. The present critical water supply situation at Waco is due to the high rate of capacity loss in the reservoir, which is causing rapid decrease in storage capacity, and to the rapidly rising water demand in the city.

This report is based upon the results of three detailed surveys of sedimentation in Lake Waco, made in 1935, 1936 and 1947 respectively. The 1935 and 1936 surveys were part of a comprehensive research study of sedimentation in reservoirs of the United States by the Sedimentation Section of the Soil Conservation Service (4). Early in 1935, within five years after construction of the dam, Waco Water Department personnel had noted considerable deposits of sediment in the headwaters of the lake and high turbidity of water passing the dam following storms. Therefore the first survey of Lake Waco was made to examine the effect of sedimentation upon the city water supply, and to obtain data on sediment production rates in a typical central Texas area. This survey, made in the period January-March of 1935, showed that the lake had lost capacity by sedimentation at the high average annual rate of 3.34 percent. During the latter part of 1935 a number of floods occurred in the Bosque River, and the city, concerned at the high rate of capacity loss, requested a second survey which was made in January-February 1936. This survey showed that 5.4 percent of the reservoir capacity had been replaced by sediment during the 11-month period since the first survey. The third survey was made in November and December of 1947 at the request of the city and in conjunction with the United States Department of Agriculture Flood Control Survey of the Bosque River Basin. It was made by a combined 6-man survey party of Soil Conservation Service and city of Waco personnel, and headed by Ross E. Rogers.

This report does not include a study of the water filtration and distribution system.

Objectives of this Investigation

The major objectives of this investigation were as follows:

1. To evaluate the present rate of sediment contribution per unit area of drainage and to compare it with past rates. This comparison might be expected to show the effects of soil conservation measures which have been applied to a considerable part of the drainage area during the past 10 years.

2. To provide a basis for estimating the long-time effects of a drainage area treatment program in prolonging the useful life of Lake Waco and similar reservoirs.

3. To determine the present capacity of Lake Waco and the probable long term average annual loss of capacity by sedimentation.

4. To forecast the date when the increase in water demand by the city and the decrease in reservoir capacity by sedimentation will require an additional impounded water supply.

RESERVOIR AND DRAINAGE AREA STUDIES

In addition to the reservoir surveys by the Soil Conservation Service, a number of other investigations of the Brazos River drainage area and studies of sites for other reservoirs have been made by various agencies. A reconnaissance erosion survey of the entire Brazos River Basin, including the Bosque River area was made by Geib and Goddard in 1933 (5). The geology and mineral resources of McLennan County were mapped and described by Adkins in 1923 (1). Most of the data on soils, erosion, and hydrology for this report were derived from surveys made by the Soil Conservation Service for a Flood Control Report on the Bosque River Basin in 1947 (2). Other sources of data are publications and file material of the Texas Board of Water Engineers, the U. S. Geological Survey and the Corps of Engineers, Department of the Army.

ACKNOWLEDGMENTS

A number of agencies and persons have contributed to the data presented in this report. The Waco Water Department, headed in 1935-36 by George J. Rohan, and in 1947 by Hubert G. Davis, provided all information on operation of the reservoir, water use by the city, and turbidities at the filter plant. The same department also furnished office facilities for work on maps and notes and assisted Soil Conservation Service personnel in completing the 1947 survey. F. H. Husbands, Secretary, and George Logan, Agricultural Manager, Waco Chamber of Commerce, furnished data on city population and industries. The District Office of the Corps of Engineers, Department of the Army, supplied information on hydrology from a report on flood control and reservoir sites in the Bosque River Basin. Some of the records on early history of the Waco Water Department were obtained from reports by the Pitometer Company, Engineers, of New York City (7). Details on construction of the dam were furnished by J. L. Lockridge of Floyd and Lockridge, Consulting Engineers, Dallas, Texas.

LAKE WACO DAM AND RESERVOIR

The Dam

Lake Waco dam is on the Bosque River, 4.2 valley miles above its junction with the Brazos River in McLennan County, Texas (figure 4). It is located 4-1/2 miles west of the Waco Municipal Building. An asphalt road provides all-weather access to the dam from Waco and extends across the length of the dam. Construction of the dam was completed and storage began in April, 1930.

The dam is of earth-fill type, constructed of the most suitable clays of the Eagle Ford formation from the adjoining valley bottom and slopes. It is approximately 4,700 feet long. The upstream slope of the dam is faced with 6 inches of concrete underlain by a 6-inch gravel blanket. The upstream slope of the dam from the base to spillway crest, elevation 430.0 feet, is 3 to 1 and from elevation 430.0 to 440.0 it is 2.5 to 1. A slope of 1.5 to 1 extends from elevation 440.0 to the asphalt road on top of the dam at elevation 442.0. From the base of the dam on the downstream side, the slope is 3:1 up to an 8-foot berm designed for draining the 2:1 slope above. Thickness of the dam at its base varies with the topography.

The Spillway

The spillway section is constructed of concrete with vertical concrete wingwalls at each end. It has a concrete apron at the downstream toe which is 57 feet below crest elevation. Flow through the spillway is controlled by 16 Taintor gates each 25 feet wide and 15 feet high. The gates are separated by concrete piers 3 feet wide. Elevation of the gate sills is 415.0 feet. The tops of the gates are 430.0 feet elevation when closed.

Two concrete sluice outlets pass through the spillway at bottom elevations of 382.6. Each outlet is 6.0 feet wide with vertical walls 7.25 feet high and an arched roof affording an additional 1.5 foot vertical clearance. The outlets are equipped with metal gates set in vertical guides for opening and closing. They were built for the purpose of sluicing silt out of the lake but have not been used for several years because of difficulty in getting them completely closed after opening.

The total original cost of the dam and land acquired for the lake was approximately $2,000,000. Water flowing through the spillway undermined the concrete apron at the spillway base and eroded a cavity in the soft underlying Eagle Ford shale which endangered the entire spillway section by 1946. Repairs, consisting of filling in the undermined section, extending the apron and constructing a vertical concrete footing at the end of the apron, cost approximately $425,000.

The Reservoir

The reservoir immediately upstream from the dam is a broad basin with gently sloping sides and nearly flat bottom except for the channels (figures 2 and 3). It has an area of about 1,200 acres, nearly half of the total lake area. The North and South Bosque River channels join near the center of this basin about 3,300 feet upstream from the dam. Upstream from the central basin, the reservoir divides into two main arms of nearly equal area formed by the valleys of the North and South Bosque Rivers. The North Bosque arm is about 6.6 miles in length and the South Bosque arm about 7.0 miles in length. Neither arm has been shortened by sediment deposits at its head. Each arm has an upstream ponded channel section approximately as long as the wide water area below it (figure 22).

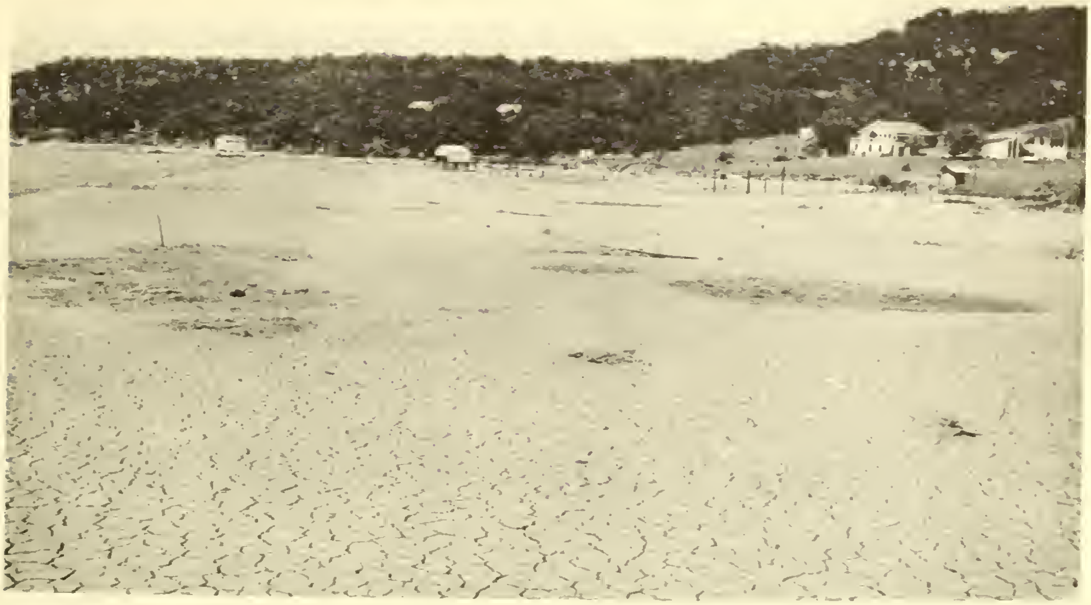


Fig. 2 Sediment deposit in South Bosque arm of Lake Waco below Highway 6 bridge. Water 7 feet below crest.

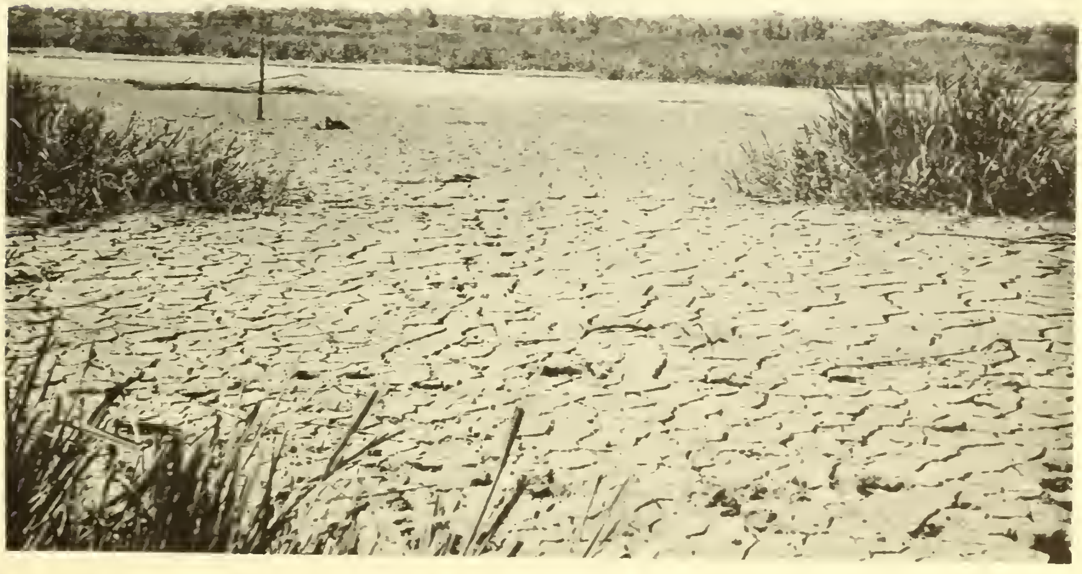


Fig. 3 Sediment deposit near north shore of South Bosque arm, Lake Waco.

The original area of the lake as measured by the 1936 survey was 2,801 acres and the original capacity was 39,378 acre-feet. The maximum original depth of water measured in 1936 was 43.2 feet.

Steep bluffs as much as 30 feet in height form the shoreline for short distances in several locations on each arm of the lake. In some areas the bases of moderately steep valley slopes approach to within a few hundred feet of the lake. Along the remaining shoreline, long slopes of moderate grade extend from the upland down to the lake shore.

THE DRAINAGE AREA

Physiography and Geology

General features. The Lake Waco drainage area includes parts of McLennan, Coryell, Bosque, Hamilton, Somervell, and Erath counties in central Texas (figure 4). It has an extreme length of about 90 miles, an average width of approximately 20 miles, and is roughly rectangular in shape. The Bosque River system drains a total area of 1,676 square miles (8) nearly all of which (1,666 square miles) lies upstream from Lake Waco Dam. The main stream joins the Brazos River about five miles by channel in an easterly direction from the dam. The two main tributaries are the North and South Bosque Rivers which join within the lake area. The two major tributaries of the South Bosque River are Middle Bosque River and Hog Creek. The major tributaries of the North Bosque River, in order upstream, are Neil Creek, Meridian Creek, East Bosque River, Little Duffau Creek, Greens Creek, Alarm Creek, and the North Branch of the Bosque River.

Parts of two major physiographic provinces, the Great Plains and the Coastal Plain, are drained by the Bosque River and tributaries. Elevations in the area range from nearly 1,700 feet above sea level on the outermost rim of the North Bosque drainage in northern Erath County to about 380 feet in the channel at the junction with the Brazos River at Waco. The North Bosque River descends from an elevation of 1,200 feet near Stephenville to about 400 feet near Waco in 136 river miles at an average gradient of 5.8 feet per mile. Most of the shorter tributaries have even steeper gradients. A moderate, general uplift of the Edwards Plateau and Grand Prairie regions in relatively recent geologic time has caused most streams of the area to incise their channels, hence erosion is the dominant process. The drainage pattern is generally dendritic and well developed. Rock structures are relatively simple, and all formations have gentle prevailing dips in a southeasterly direction.

Southern Great Plains Province. Approximately 94 percent, or 1,575 square miles, of the Lake Waco drainage area lies within the West Cross Timbers and the Grand Prairie belts of the Southern Great Plains Province (figure 4). An area of 233 square miles, or 14 percent of the total drainage, is in the West Cross Timbers belt in Erath County. The soils and topography of this area were developed upon the surface of the Travis Peak, or Basement Sand formation of the Trinity Group of Lower Cretaceous

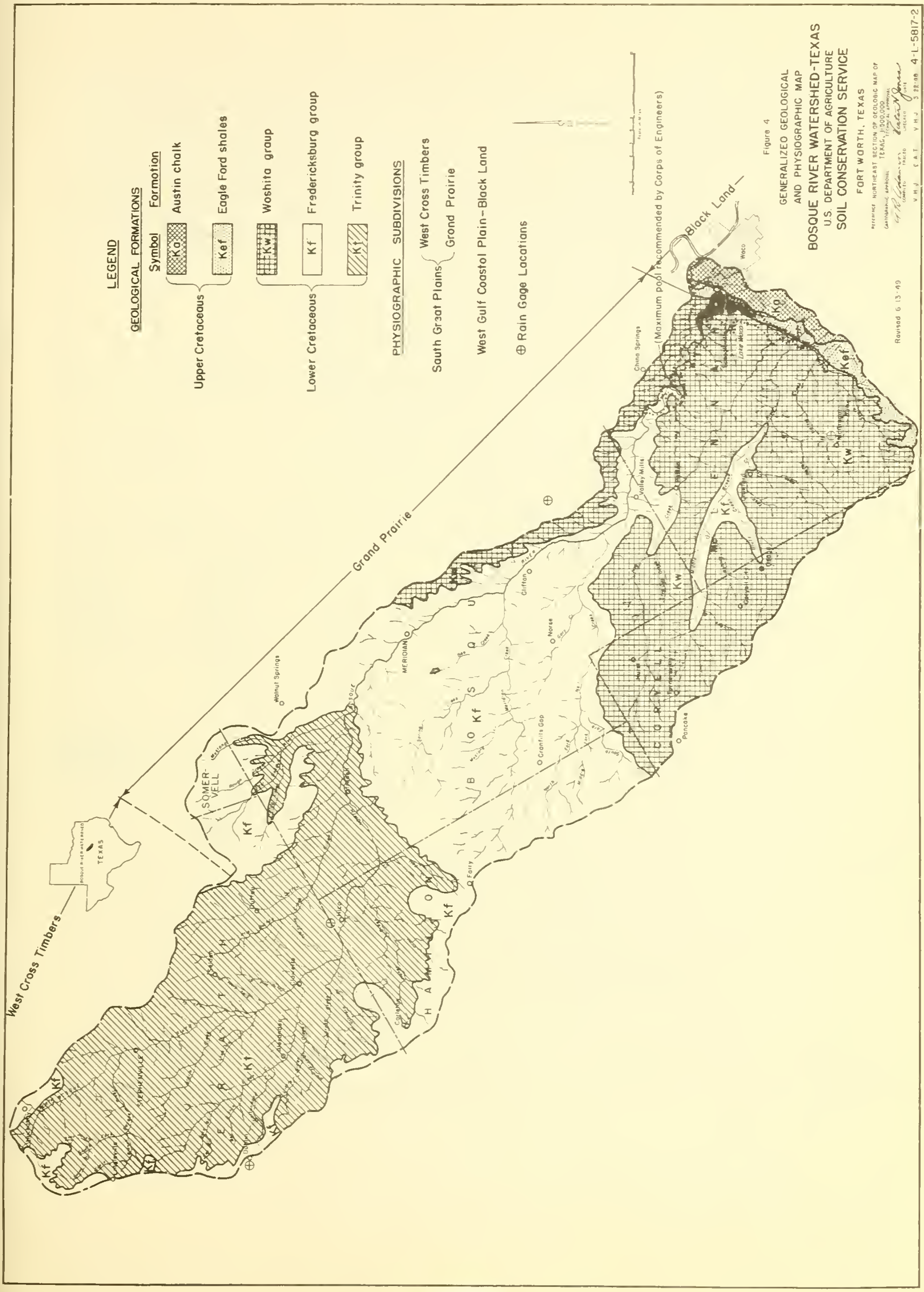


Figure 4

GENERALIZED GEOLOGICAL AND PHYSIOGRAPHIC MAP

BOSQUE RIVER WATERSHED-TEXAS

U.S. DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE

FORT WORTH, TEXAS

REFERENCE NORTHEAST SECTION OF GEOLOGIC MAP OF TEXAS, 1:500,000

AGR-SCS FT WORTH, TEX SEPTEMBER,1952

age (table 1). The undulatory land surface is interrupted in numerous places by low buttes or erosional remnants of the Glen Rose limestone around which the local relief ranges from 100 to 300 feet. The poorly consolidated sand and its overlying soils are subject to rapid destruction in cultivated areas by both sheet and gully erosion. The West Cross Timbers is a major source of sandy sediment, and valleys of the area have suffered substantial damage by accelerated Modern deposition. It is not a major source of Lake Waco sediment, however, because of its distance from the reservoir and the relatively coarse texture of the eroded sediment.

Table 1 - Stratigraphic table of rock formations in the Lake Waco drainage area

Age	Group	Formation	Lithology	Approximate thickness Feet
Quaternary		Alluvial	Clays, silts, sands and gravels in flood plains and terraces	0 - 70
UPPER CRETACEOUS	Austin		Chalk, marl, and argillaceous limestone	425
	Eagle Ford	Eagle Ford	shales, gray to black, thin limestones and bentonite	125-175
LOWER CRETACEOUS	Washita	Buda-Del Rio	Clay with thin limestone beds	75
		Georgetown	Alternating limestone, marl, shale and clay beds	235
	Fredericksburg	Edwards	Medium to hard white limestone	50 - 100
		Comanche Peak	Limestone with marly and chalky beds	40 - 80
		Walnut	Clays, marls and thin shell-limestone beds	100 - 180
	Trinity	Paluxy	Sand with thin shale and limestone beds	10 - 30
		Glen Rose	Limestone with soft marly and sandy beds	50
		Travis Peak (Basement Sands)	Basal conglomerate overlain by sands	200 - 250

Sources: Texas Bureau of Economic Geology and U.S.G.S. maps and publications.

The greater part of the drainage area (81 percent) lies within the Grand Prairie belt. The North Bosque River and its tributaries enter the Grand Prairie near the south line of Erath County, flow entirely across it, and enter the Gulf Coastal Plain about five miles northwest of Waco. All rock formations at and near the surface are predominantly flat-lying or gently-dipping beds of limestone and shale of the Fredericksburg and Washita groups of Lower Cretaceous age, and the Glen Rose limestone of the Trinity group (table 1).

The western half of the Grand Prairie, in northern Bosque, eastern Hamilton and southern Somervell counties, corresponds roughly to the outcrop area of the Fredericksburg group, and has some characteristics of a plateau. It has a local relief of 300 to 400 feet, especially in northern Bosque County, where buttes and flat-topped divides, bordered by limestone cliffs, are scenic features. The valleys are deep and narrow in many places, and the channels display extensive limestone outcrops in beds and banks. This is the northern extension of the Lampasas Cut Plain, which is even more conspicuously developed southward in the Little River Basin. The eastern part of the Grand Prairie in McLennan and southern Bosque counties is lower and more gently sloping, and the local relief rarely exceeds 200 feet.

Erosion rates in the Grand Prairie are generally lower than in the West Cross Timbers and Black Prairie belts. In the Lampasas Cut Plain the steepest slopes are rocky bluffs, bottomlands and uplands are relatively flat, and most of the land is used for pasture. The sediment carried by runoff waters is chiefly silt and clay derived by sheet erosion plus limestone gravel from channel erosion. Gully development is limited in most places by resistant underlying limestone formations. In the eastern part of the Grand Prairie much larger quantities of silt and clay are carried by runoff waters from extensive cultivated areas of the dark clay soils. The Del Rio formation, a calcareous clay, occurring at the surface in north central McLennan County has soils similar to those of some Black Prairie areas.

West Gulf Coastal Plain Province. The Black Prairie is the only division of the West Gulf Coastal Plain which occurs in the Lake Waco drainage area. It occupies about four percent of the Bosque River Basin in a narrow belt along the southeast margin. The northern part of the belt is underlain by the Eagle Ford shale, which has some thin limestone and shell beds, and the southern part is underlain by the Austin chalk. The edge of the Austin formation forms a prominent bluff or cuesta, facing northwesterly, extending to the southwest from the Brazos River Valley along the south shore of Lake Waco and beyond the South Bosque River headwaters. Both gully and sheet erosion have developed seriously in the black clay soils of the sloping cultivated areas along the Bosque Escarpment. Consequently large volumes of clay and silt are carried by streams from this source into Lake Waco.

Soils and Erosion

Because of their great extent, the soils of the Grand Prairie are predominant in the Bosque River Basin. They are chiefly brown or black clays developed upon limestone or calcareous clay. In the northwestern half of the Grand Prairie (Lampasas Cut Plain) the upland soils are mostly thin and rocky, and many of the steeper bluff faces have practically no soil mantle. In the southeastern half, the soils are thicker and more mature, and hence are more suitable for cultivation.

The soils of the West Cross Timbers have more variety, but loose sandy topsoils predominate. Subsoils in most places have a sandy clay texture, and are relatively infertile. Erosion by both water and wind has caused severe damage to large areas of unprotected cultivated land in this section.

The soils of the Black Prairie surround Lake Waco and extend upstream in a narrow belt along the south margin of the South Bosque drainage. The soils are chiefly black clays, and their high original fertility has resulted in extensive cultivation on many of the steeper slopes as well as on flatter areas.

A tabulation of conservation survey data from the four Soil Conservation Districts which cover the drainage area showing the distribution of the main soil groups, according to physiographic area follows (table 2).

Table 2 - Major soil groups in the Bosque River Basin

Physiographic area	Major soil groups	Percentage of area
West Cross Timbers	1. Deep, medium-textured, moderately permeable	56
	2. Coarse-textured, permeable	33
	3. Other types	11
Grand Prairie	1. Deep, fine-textured, slowly permeable	35
	2. Shallow soils	31
	3. Shallow and stony	26
	4. Other types	8
Black Prairie	1. Deep, fine-textured, slowly permeable	62
	2. Deep, fine-textured, permeable	9
	3. Shallow soils	6
	4. Alluvial	14
	5. Other types	9

A study of soil losses and soil decline in the drainage area has been made by the Conservation Survey Division of the Fort Worth Regional Office of the Soil Conservation Service. Data on soil erosion were assembled from experiment station records, land-use patterns, and various soil and erosion surveys. Table 3 shows a summary of annual soil loss, or soil decline, factors as related to sedimentation in Lake Waco. All data now available indicate that the Black Prairie and cultivated Grand Prairie areas contribute the greatest amount of sediment per unit area, because of their close proximity to the reservoir, the fine texture of the sediment, and the relatively high rates of erosion in those areas. Actual erosion rates in the entire basin range from about 4.0 acre-feet per square mile annually in the severely eroded Black Prairie to about 1.0 acre-foot in the Grand Prairie range land, but only approximately 25 percent of the eroded material reaches the reservoir.

Land Use and Conservation Programs

A recent study of land use in the Bosque River Basin above Lake Waco is summarized in table 4. These figures, from recent soil conservation district data, show that nine percent of the total drainage area is classified as nonfarm land. Of the farm land, 42 percent is cultivated and 56 percent is open grassland or woodland pasture. The South Bosque River drainage area, which includes most of the cultivated Grand Prairie and Black Prairie within the basin, has approximately twice the proportion of cultivated land as that in the North Bosque.

Several factors involving farm operation and economy have had some influence upon rates of erosion and sediment production during the life of Lake Waco. A reduction in cotton acreage and an increase in pasture land have occurred since about 1934 under the influence of the various agricultural programs. It is estimated from census and soil conservation district data that a total area of about 200,000 acres (312 square miles) in the drainage area was converted from clean-tilled crops to pasture during a 14-year period. Since 1930 the average size of farms has increased from 198 to 233 acres, and since 1934 the average income per farm has increased substantially. In general these factors promote better care of farm lands, and tend to reduce erosion rates. Another favorable factor is the decrease in tenant farming from 44 percent of the total farm land in 1930 to 28 percent in 1945. One unfavorable factor during the war years was an increase in cropland devoted to growing of peanuts in the West Cross Timbers belt. This area, however, is remote from Lake Waco, and probably had little effect upon sedimentation in the reservoir. Probably the most important factor favorable to reduction of erosion rates is the installation of complete conservation works upon about 10 percent of the drainage area. This has been accomplished since 1935 under the soil conservation district program.

METHODS OF SURVEY

Original Survey

A survey of Lake Waco dam site and shore line was made prior to construction of the dam. The estimated capacity of the lake from this survey

Table 3 - Relationships of soil loss factors in the Bosque River Basin to sedimentation in Lake Waco [1]
(Estimated sheet erosion)

Sub-Areas	Percentage of sub-tributary	Estimated annual soil loss	Estimated annual total soil loss	Contribution to Lake Waco per acre per sq.mi.		Percentage of total sediment
		Tons Per Acre	Tons	Tons	Acre-Feet [2]	
North Bosque Drainage						
West Cross Timbers	18.5	3.8	570,130	1.0	0.50	12.0
Grand Prairie						
Cultivated	34.4	6.7	1,866,400	1.6	0.80	35.8
Range	27.9	1.0	226,000	0.2	0.10	3.6
Wooded	17.5	4.5	636,270	0.9	0.45	10.2
Black Prairie	1.5	8.4	99,950	3.2	1.61	3.0
Totals			3,398,285		0.50	64.6
South Bosque Drainage						
Grand Prairie						
Cultivated	65.2	6.7	1,121,860	1.6	0.80	21.3
Range	4.2	1.0	10,680	0.2	0.10	0.2
Wooded	14.5	4.5	166,914	0.9	0.45	2.6
Black Prairie						
Normal	5.4	8.4	183,070	3.2	1.61	5.4
Severely eroded	10.4	14.4	268,290	4.0	2.00	5.9
Totals			1,750,812		0.86	35.4
Grand Totals and Averages		4.8	5,149,097	1.2	0.59	100.0

---

[1] Compiled by Arnold H. Bean, Soil Conservationist, Soil Conservation Service, Fort Worth, Texas.

[2] Based upon a weight per cubic foot of 58.5 pounds as determined from analysis of 12 samples.

Table 4 - Distribution of various types of land use in 1948 in the Bosque River Basin

Sub-Area	Extent of area	Nonfarm land	Farm Land: Cultivated	Farm Land: Open grassland	Farm Land: Woodland pasture	Farm Land: Miscellaneous
	Sq. mi.	Percent	Percent	Percent	Percent	Percent
North Bosque						
West Cross Timbers	234.4	2.6	47	50	2	1
Grand Prairie	1,009.3	9.0	30	48	20	2
Black Prairie	18.6	3.3	72	16	8	4
Totals	1,262.3	7.8	34	48	16	2
South Bosque						
Grand Prairie	336.3	12.3	66	20	12	2
Black Prairie	63.1	10.1	73	19	5	3
Totals	399.4	11.9	67	20	11	2
Lake Waco	4.3	100.0	-	-	-	-
Grand Totals	1,666.0	9.0	42	41	15	2

was 38,500 acre-feet and the area 2,700 acres. The lake area was mapped at a scale of 2,000 feet to the inch. Seven widely spaced cross sections of the lake were originally established but most of the monuments are now lost or destroyed.

Surveys of 1935 and 1936

A sedimentation survey party of six men under the direction of Thomas L. Kesler, party chief, was sent to Waco early in 1935 to make the first sedimentation survey of Lake Waco by the Soil Conservation Service. Field work was begun on January 15 and completed late in March. It was decided that the original shoreline map was on too small a scale to show sufficient detail and that a new shoreline map should be made. The original cross sections of the lake were spaced at such great intervals that they appeared to be of little value for a detailed sedimentation survey, hence they were not included in the range network for the 1935 survey.

A baseline 4,200 feet in length was chained and checked along the roadway on top of the dam for use in establishing horizontal control around the lake. From this line 16 additional triangulation stations were established by plane table and telescopic alidade. Using the triangulation stations as control points the shoreline was mapped on plane table sheets at a scale of 1,000 feet to the inch. A contour at elevation 432.0, two feet above crest, was also mapped, and 33 sediment ranges were established across the lake. Soundings were taken on the range lines with a sounding

weight attached to a copper-cored sounding line marked at 1.0 foot intervals. Measurements of sediment thickness were obtained by use of the standard spud, or sediment measuring bar (4). On most ranges the position of the sounding or spudding was cut in by intersection from a plane table located on a suitable cut-in station. On several ranges where the lake was confined mainly to the original river channel, locations of measurements were obtained by reading stadia distance with a transit set up on one end of the range. All range-ends and other important survey stations were marked permanently in the field by iron pipe set in concrete, with the top of pipe generally set about 0.5 foot above ground.

Cross sections were plotted from the sounding and spudding notes showing the profile of the lake bottom at date of survey and the original profile. The areas enclosed by these cross sections at spillway level, and segment areas between ranges were determined by planimetering. From these data the original capacity and sediment volume for all segments of the reservoir except the one nearest the dam were determined by the Soil Conservation Service range survey formula (4). The range nearest the dam (range 01 - 02) appeared to be so close to the dam that it crossed areas excavated by construction. The average original depth was combined with the average depth of range 03 - 04 in computing the original capacity but the sediment measurements were disregarded. The original capacity and sediment volume of that segment were computed by multiplying surface area by average depths.

A six-man party under the direction of Louis M. Glymph, Jr., made the second survey. The field work was done during the period January 13 to February 20, 1936. Since a shoreline map had been made in 1935 it was not necessary to remap the shore line in 1936. The ranges established in 1935 were again sounded and spudded. Three additional ranges were established and measured during the 1936 survey to increase the accuracy of volume measurement. The new range ends were marked with iron pipe in the same manner as on the previous survey. Seven shoreline ranges were established for future determination of the extent of wave erosion as a factor in sedimentation of the reservoir (see figures 5 and 6)

New cross sections showing the original and present profiles were plotted from the 1936 field data and the areas planimetered. The original capacity and sediment volume were recomputed by the range-survey formula mentioned previously, using the 1936 cross-section data. Range 01 - 02 was disregarded in computing the volume of the segment nearest the dam in 1936. Average depths on range 03 - 04 were multiplied by the surface area of the segment to arrive at the original capacity and sediment volume of the segment because range 01 - 02 was too close to the dam.

Results of the 1936 survey indicated a higher rate of capacity loss by sedimentation in the reservoir than that found in 1935. This was probably caused by the unusually heavy runoff into the lake which occurred between the two surveys. Results of these surveys are summarized with the 1947 survey results in table 6.

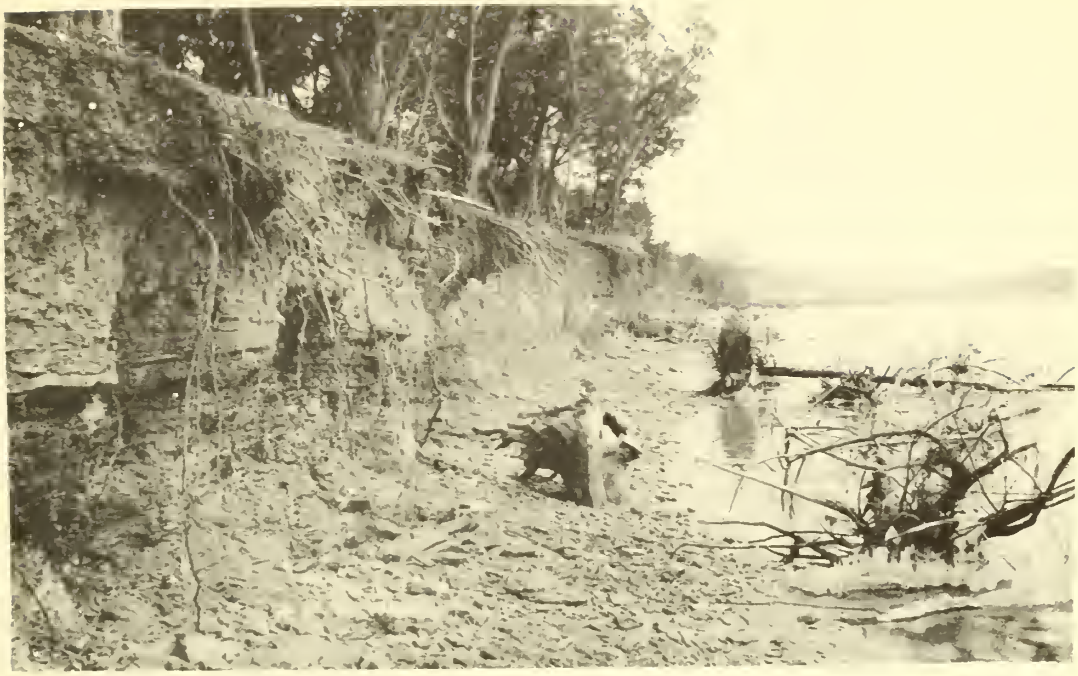


Fig. 5 Wave-cut bank on gravel terrace on Eagle Ford Shale, South Bosque arm, 1/4 mile above Hwy. 6 bridge.

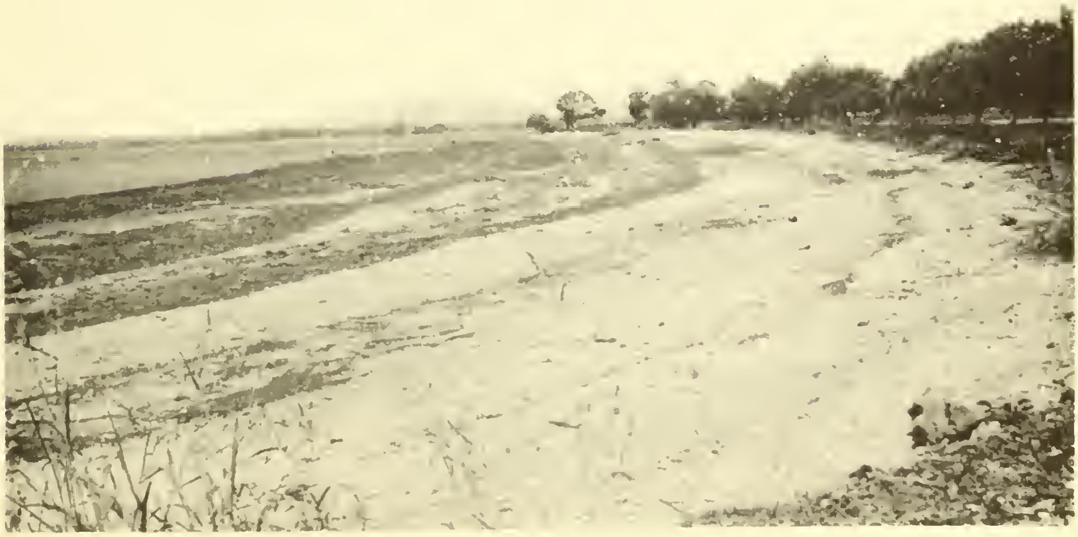


Fig. 6 Gravel beach and wave-cut bank on North Bosque arm, Lake Waco.

Resurvey of 1947

During the period November 25 - December 31, 1947 a three-man sedimentation survey party headed by Ross E. Rogers, party chief, and assisted by three men furnished by the city of Waco, made a resurvey of the reservoir. All ranges with the exception of 01 - 02, nearest the dam, were sounded. A few sediment measurements were taken by spud for check purposes. Several reaches of shoreline were remapped where scour or deposition had changed the location of the crest contour since 1936. In addition, small areas of above-crest sediment were mapped on the South Bosque arm of the lake. Three wave-erosion ranges established in 1936 were rerun. These included numbers 101, 102 and 103. The remaining wave ranges were inspected but not rerun, as no bank erosion was evident. A fairly large number of range end markers could not be located. Some had been washed out, others were evidently covered by sediment, and a few had been dug out because they were in fields or lawns. The locations of the lost markers were re-established by plane table and alidade from adjacent stations. Iron pipe with appropriate numbers stamped thereon were set at the relocated positions of range-ends 029, 031, 033, 035, 036, 039, 043, 045, 054 and 060. Ranges were extended back on line from relocated range-ends 010, 048 and 061 which had been washed out, and iron pipe markers were set at the ends of the extensions and marked 60, 39 and 61 respectively. A chiseled X was made on a concrete retaining wall on line with, and 23 feet farther from the lake shore than the relocated position of 06 in order to avoid placing a marker on a private lawn. A chiseled X was also made on a concrete retaining wall in line with, and 95 feet toward the lake shore from the relocated position of 08, so that it would not fall in the fairway of a golf course.

The 1947 cross section data were plotted on the cross section sheets prepared for the 1936 survey, and the present (1947) cross section areas planimetered. Surface areas were replanimetered for segments where the shoreline had changed since 1936. The present capacities of most of the segments of the lake were then computed by the range-survey formula used in 1936, by substituting present (1947) values of surface area, cross section area, and range length into the formula. Standard procedure was not followed in computing the capacities of segments 13, 15, 17, 18, 19, 28, to 34 and 37. On those segments the distances in feet between ranges were measured along the axis of the lake and the values thus obtained were substituted in the formula in place of perpendicular distances, to solve for the quadrilateral areas of the segments.

Cross section areas and surface areas of above-crest sediment were planimetered and their quantities computed by the range-survey formula. The total quantity of above-crest sediment measured was 54 acre-feet, a negligible proportion of the total sediment within the lake basin.

In order to obtain a distribution of capacities at various stages of the lake, contour maps of the lake bottom in 1930 (original), 1936, and 1947, were prepared and the capacities on these dates were computed by the contour method. Contours were prepared on transparencies of the

lake-shore map at a 2-foot vertical interval from crest elevation (430 feet) to 418 feet, and at a 4-foot vertical interval from 418 feet elevation to the low point in the lake. These maps, on a scale of 1,000 feet to the inch, were constructed by plotting on the range lines the contour elevations obtained from the field notes, and drawing interpolated contours between ranges, guided by the configuration of the spillway contour. Contours were not extended up the narrow channel sections at the upper ends of the lake, but were stopped at range 037 - 038 on the North Bosque arm and range 056 - 057 on the South Bosque arm. Areas in these arms at the various contour elevations were computed on the basis of their widths at the ranges which they cut. The contoured lake areas were measured by planimetering (figures 22, 23 and 24).

Volumes of the lake at the various contour levels in 1930, 1936, and 1947 were calculated by the modified prismoidal formula:

$$V = \frac{L}{3}\left(A + \sqrt{AB} + B\right)$$

where

V = Original or remaining capacity in acre-feet.

L = Contour interval, feet.

A = Area at the lower contour, acres.

B = Area at the upper contour, acres.

The capacity of the lake at crest elevation computed by the contour method was smaller than that computed by the range-survey method in all cases, on Lake Waco. The results of the range-survey calculations were adopted as the final results.

The 1930 (original) capacity at crest elevation by the contour method was 38,309 acre-feet, or 2.7 percent less than the capacity obtained by the range method; the 1936 capacity by the contour method was 31,365 acre-feet, 0.7 percent less than by the range method; and the 1947 capacity by the contour method was 20,796 acre-feet, 5.6 percent less than by the range method. The capacities at each contour elevation determined by the contour method were multiplied by the factor 1.0279 for the 1930 lake stages, by 1.0071 for 1936, and by 1.05915 for 1947, to adjust them proportionally to the capacities determined by the range survey. The adjusted capacities at each contour elevation were as follows:

Table 5 - Capacity at contour elevations, Lake Waco

(See figure 7)

Contour Elevation	1930 (original) capacity	1936 capacity	1947 capacity
Feet	Acre - feet	Acre - feet	Acre - feet
390	38.42	-	-
394	264.90	-	-
398	744.33	-	-
402	1,611.00	4.39	-
406	2,844.34	256.12	-
410	4,518.35	1,100.69	1.71
414	7,439.52	3,010.73	204.99
418	12,507.67	6,660.04	1,221.81
420	15,971.20	9,496.26	2,466.51
422	19,923.69	13,023.90	4,651.16
424	24,198.50	16,946.99	7,726.89
426	28,803.71	21,291.05	11,744.43
428	33,842.44	26,167.60	16,570.93
430	39,377.96	31,588.00	22,026.00

UNITED STATES
DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

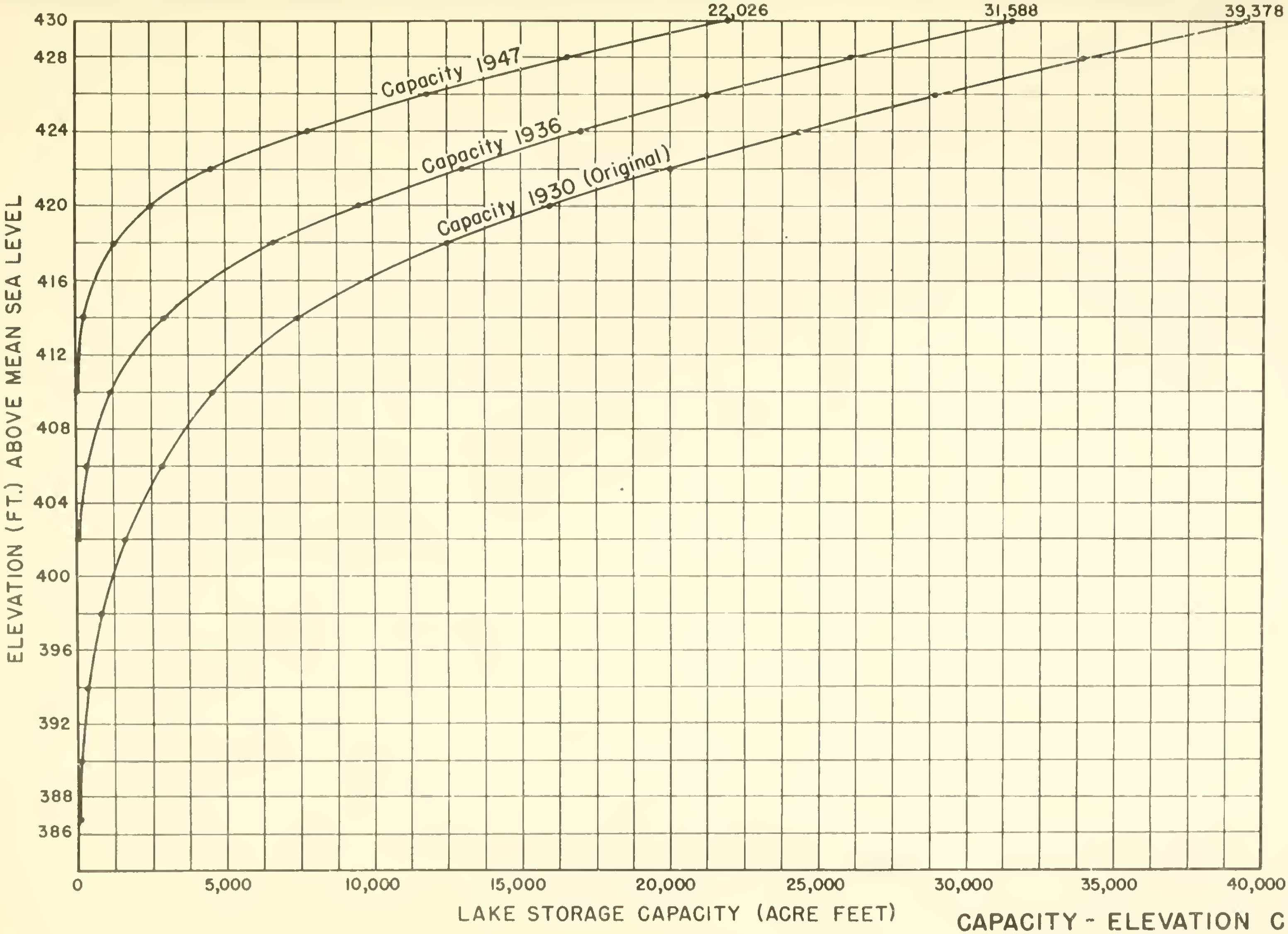


FIGURE 7

CAPACITY - ELEVATION CURVES
OF LAKE WACO
TEXAS

10-26-48 C.M.D. 4-L-6955

AGR SCS FT WORTH,TEX SEPTEMBER,1952

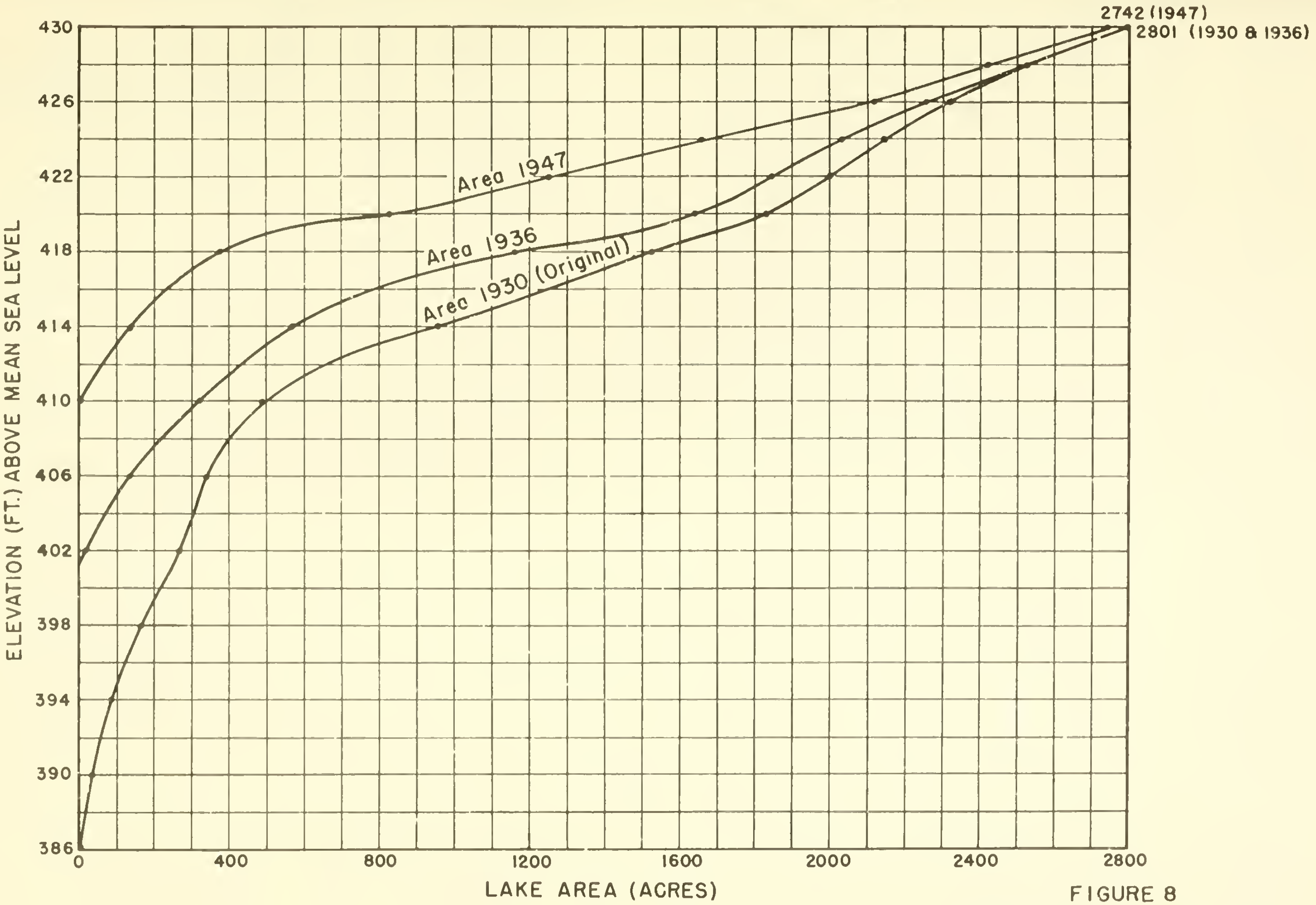


FIGURE 8
AREA - ELEVATION CURVES
OF LAKE WACO
TEXAS

10-27-48 C. M. D. 4-L-6958

AGR SCS FT WORTH,TEX SEPTEMBER,1952

Curves showing the area and capacity of the lake at various stages were constructed from these adjusted data and are shown as figures 7 and 8.

SEDIMENTATION IN THE RESERVOIR

Rates of Sedimentation

For the study of drainage-area influences on sedimentation in Lake Waco, the two periods, 1930-1936 and 1936-1947, have been used, although three complete sedimentation surveys of the reservoir have been made. The first period, of 5.9 years, extends from April 1930, when storage in the reservoir began, to February 1936, the median date of the second (1936) survey (table 6). The average annual rate of capacity loss for this period was 3.35 percent, or 1,320 acre-feet, and this includes a high runoff period of 12 months during which 2,129 acre-feet of sediment were deposited in the basin. The second period, of 11.8 years, extends from February 1936 to December 1947, the median date of the third survey. For this period the average annual rate of capacity loss was 2.06 percent, or 810 acre-feet. Therefore the annual rate of capacity loss since 1936, as determined by reasonably accurate measurements of the deposit, has been 38.6 percent less than during the earlier period 1930-36. The total loss of capacity during the life of the reservoir, to 1947, has been 44.07 percent or 17,352 acre-feet.

Table 6 - Summary of sedimentation data on Lake Waco

	Quantity	Unit
Age: 1/		
1930-1935	4.9	Years
1935-1936	1.0	Years
1936-1947	11.8	Years
1930-1947	17.7	Years
Drainage Area:		
Total area 2/	1,666	Sq. miles
Reservoir:		
Area at spillway stage:		
1930, 1935 and 1936	2,801	Acres
1947	2,742	Acres
Storage capacity at spillway stage:		
1930	39,378	Acre-feet
1935	33,717	Acre-feet
1936	31,588	Acre-feet
1947	22,026	Acre-feet
Capacity per square mile of drainage area 2/		
1930	23.64	Acre-feet
1935	20.24	Acre-feet
1936	18.96	Acre-feet
1947	13.22	Acre-feet

Table 6 - Summary of sedimentation data on Lake Waco (continued)

	Quantity	Unit
Sedimentation:		
Total sediment: 3/		
1930-1935	5,661	Acre-feet
1935-1936	2,129	Acre-feet
1936-1947	9,562	Acre-feet
1930-1947	17,352	Acre-feet
Average annual accumulation:		
From entire drainage area:		
1930-1935	1,155	Acre-feet
1935-1936	2,129	Acre-feet
1936-1947	810	Acre-feet
1930-1947	980	Acre-feet
Per square mile of drainage area: 4/		
1930-1935	0.695	Acre-feet
1935-1936	1.281	Acre-feet
1936-1947	0.487	Acre-feet
1930-1947	0.590	Acre-feet
Per acre of drainage area: 4/		
By volume:		
1930-1935	47.30	Cubic feet
1935-1936	87.19	Cubic feet
1936-1947	33.17	Cubic feet
1930-1947	40.13	Cubic feet
By weight: 5/		
1930-1935	1.38	Tons
1935-1936	2.55	Tons
1936-1947	0.97	Tons
1930-1947	1.17	Tons
Sediment concentration: 6/		
1930-1935	0.388	Percent
1935-1936	0.402	Percent
1936-1947	0.175	Percent
1930-1947	0.233	Percent
Depletion of storage:		
Loss of original capacity:		
Per year:		
1930-1935	2.93	Percent
1935-1936	5.41	Percent
1936-1947	2.06	Percent
1930-1947	2.49	Percent
Total:		
1930-1935	14.38	Percent
1935-1936	5.41	Percent
1936-1947	24.28	Percent
1930-1947	44.07	Percent

Table 6 - Summary of sedimentation data on Lake Waco (continued)

1/ Storage began April 1930. Median dates of surveys: February, 1935; February, 1936; and December, 1947.
2/ Including area of lake.
3/ Sediment volumes shown for 1936-1947 and 1930-1947 do not include 54 acre-feet of above crest sediment found on the 1947 survey.
4/ Excluding area of lake.
5/ Based on an average dry weight of 58.5 pounds per cubic foot as determined from 9 undisturbed samples taken in 1947.
6/ Based on estimated annual flow into Lake Waco, Table 10.

Character of the Sediment

The greater part of the sediment in Lake Waco basin is gray to dark gray clay, with minor fractions of silt and fine sand. This deposit is almost uniformly fine-textured, loosely compacted and highly porous all over the main lake basin and both North and South Bosque arms to range 031-032 and 035-036 respectively (see Reservoir Maps, figures 22, 23, and 24). The tabulation of data on the 9 samples of bottom sediment, taken December 31, 1947 (table 7 and figure 9) shows that all samples except W8 are clays. Sample W8 is an argillaceous sand, obtained in shallow water near 08, and represents the submerged part of a beach formed by wave action on a sand and gravel terrace. The sand is predominantly calcareous and occurs in varying proportions in the margin of the reservoir deposit around the lower part of the lake. These beaches within about 100 feet of the usual shore line also contain coarse sand and limestone gravel derived from the terraces (figure 6). Other coarse sand and gravel deposits have accumulated during floods in the form of bars from crest level to about 15 feet above it along the impounded channels of both arms of the lake above ranges 039-040 and 056-057. Relatively little of the sand and gravel has accumulated below crest level, and it has not had a substantial effect in reducing the capacity of the reservoir.

Great quantities of vegetal debris, ranging from large logs to leaves and twigs, are carried into Lake Waco by floods (figure 10). Much woody material is interbedded, in zones from less than one inch to several inches in thickness, with clays and silts in deltas of both North and South Bosque arms. At times the accumulation of driftwood obstructs the beaches around the main part of the lake, and logs occasionally interfere with operation of the Taintor gates at the spillway. No attempt was made to estimate the total quantity of woody debris in the sediment deposit (figure 11).

Laboratory analyses of 9 well-distributed samples of bottom sediment, obtained December 31, 1947 (table 7) show that the dry weight per cubic foot ranges from 42.2 to 75.9 pounds, with an average of 58.5 pounds. This figure may be slightly less than a true average since most of the samples were taken from the upper part of the deposit. The correct average figure may be as high as 60 pounds. This is a normal state of compaction

Table 7 - Data on sediment samples from Lake Waco 1/

Sample No.	Water Depth	Depth of Sampling 2/	Sediment Thickness	Location of Sample 3/	Texture 4/			Dry Weight
					Clay	Silt	Sand	
	Feet	Feet	Feet		Percent	Percent	Percent	Pounds
W-1	10.0	1.5	3.7	Range 05-03; 1700 ft.from 05	76	21	3	42.22
W-2	9.6	1.5	19.3	Range 05-03; 3700 ft.from 05	54	32	14	55.15
W-3	9.7	2.0	20.7	Range 011-010; 2420 ft.from 011	60	26	14	49.33
W-4	10.5	2.0	6.0	Range 011-010; 1020 ft.from 011	80	16	4	42.22
W-5	6.2	2.5	10.0	Range 016-017; 1040 ft.from 016	70	22	8	45.59
W-6	2.8	1.0	12.8	Range 016-017; 845 ft. from 016	57	23	20	70.06
W-7	7.4	2.0	6.0	Range 018-019; 530 ft. from 018	- 5/	-	-	72.37
W-8	7.0	2.0	12.0	Range 08 - 09; 700 ft. from 08	32	17	51	73.72
W-9	5.0	1.0	26.3	Range 08 - 09; 1435 ft. from 08	50	27	23	75.94

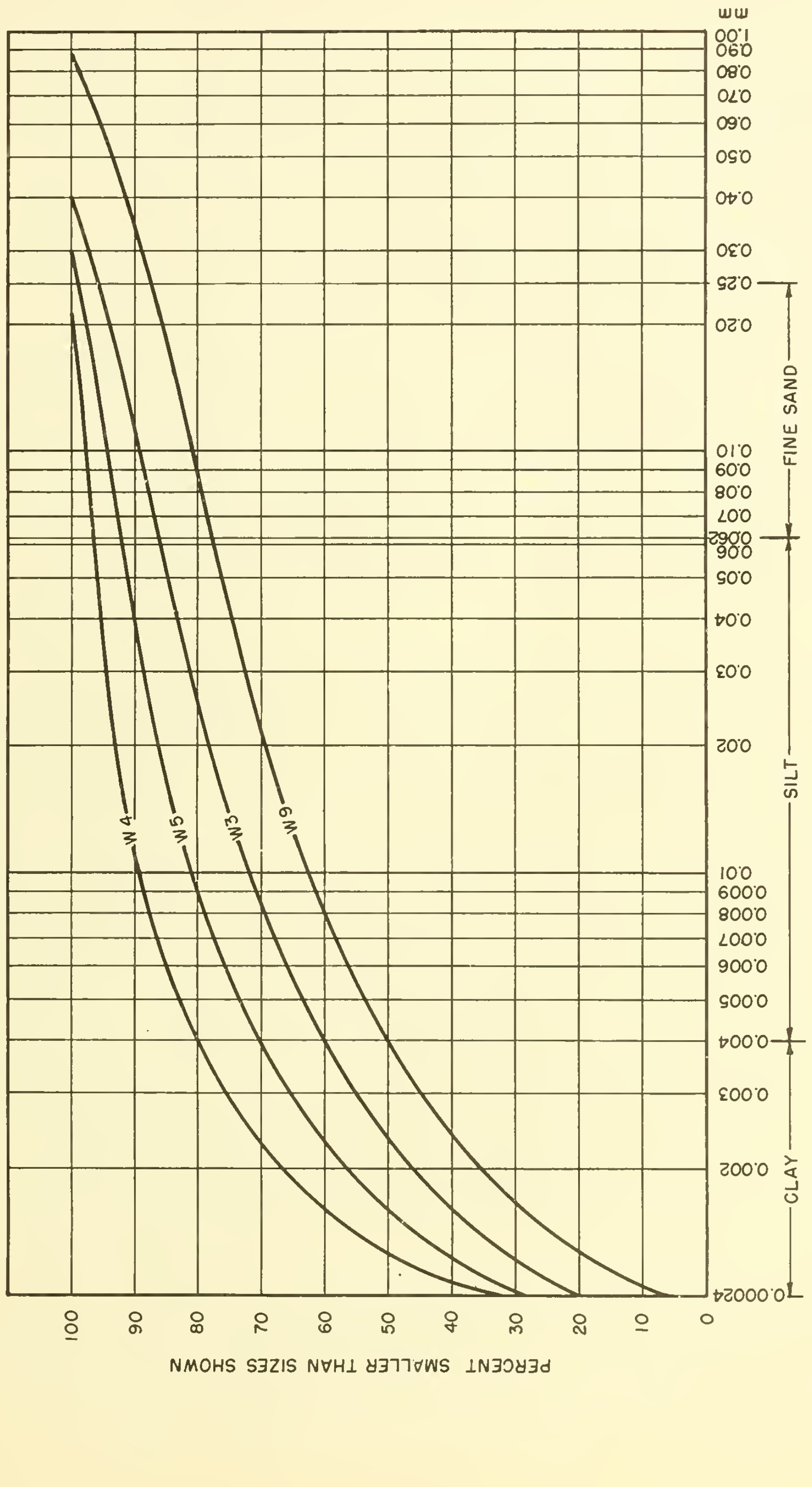
1/ Date of sampling - Dec. 31, 1947.

2/ Below sediment surface.

3/ See Reservoir maps, figs. 22, 23, and 24.

4/ Texture divisions; Clay - less than 0.004 mm., silt - 0.004 to 0.062 mm., sand - more than 0.062 mm.

5/ No mechanical analysis, not deflocculated.



Cumulative Curves Showing Textures of Typical Sediment Samples from Lake Waco. 1947 Survey.

FIGURE 9

TEXTURES OF SEDIMENT SAMPLES
LAKE WACO
TEXAS

1/10/49 A.R.A. 4-N-7082

AGR-SCS-FT WORTH, TEX SEPTEMBER, 1952

for sediment in reservoirs which have not been drawn down to low stages repeatedly for long periods. Lake Waco water level has been as low as eight feet below crest on two occasions for one- to two-month periods during repairs to the dam. Its usual water level is within two to three feet of spillway crest.

The distinction between the reservoir deposits and the pre-lake valley surface is good in nearly all places. On the submerged valley bottom and terraces the saturated, relatively homogeneous lake clays overlie dark gray to black clay and clay-loam soils. In practically all places the contact between lake clays and soils was readily distinguishable on the spud. In the channels the lake clays overlie limestone gravels, calcareous sands, and, in a few places, the compact Eagle Ford shale.

Distribution of the Sediment

The reservoir is in a fairly advanced stage of sedimentation, and is nearly 50 percent depleted. Substantial thicknesses of sediment occur over the entire bottom except narrow shore zones scoured by wave action and the narrow, upper channel segments where flood currents cause intermittent scour. Table 8 shows the distribution of storage capacity and sediment volumes in the various parts of the reservoir basin on two survey dates, 1936 and 1947. Figure 12 shows seven typical cross sections of the reservoir.

In general the sediment deposit in Lake Waco has a normal distribution for an impounding reservoir in which the water level is relatively stable. In 1936 the maximum sediment thickness found was 22.5 feet, and was located in segment 4 (reservoir map, figures 22, 23 and 24) beneath a crest-level water depth of 22.5 feet. During the 1947 survey the maximum thickness measured was 33.5 feet, in segment 3, beneath a water depth of 10.3 feet, indicating that the locus of heaviest deposition has moved downstream toward the dam. The profiles of the channels and the average water depths on ranges in the reservoir originally, in 1936, and in 1947 (figures 13, 14, 15 and 16) further illustrate the longitudinal distribution of sediment. The common sediment thickness in the submerged channel in the larger part of the reservoir, segments 2, 3, 4 and 20, ranged from 15 to 22.5 feet in 1936, and from 25.5 to 33.5 feet in 1947. On the submerged valley flat and terraces the usual thickness in this part of the lake was about 3 feet in 1936 and 7 feet in 1947. Segments 1, 2 and 3, which had a combined original capacity of 20,608 feet, had lost 14.4 percent of their original capacity by 1936 and 39.8 percent by 1947. The proportion of capacity lost by individual segments is presented graphically in figure 17.

During the same 11.8-year period between surveys the maximum sediment thickness in segment 37 had increased from 15.5 to 25.5 feet, and the average thickness on the submerged flat and terraces had increased from about 3 to 7 feet. The lower South Bosque section, segments 20, 21, 22, 23 and 37, had lost 20.2 percent of its capacity by 1936 and 39 percent

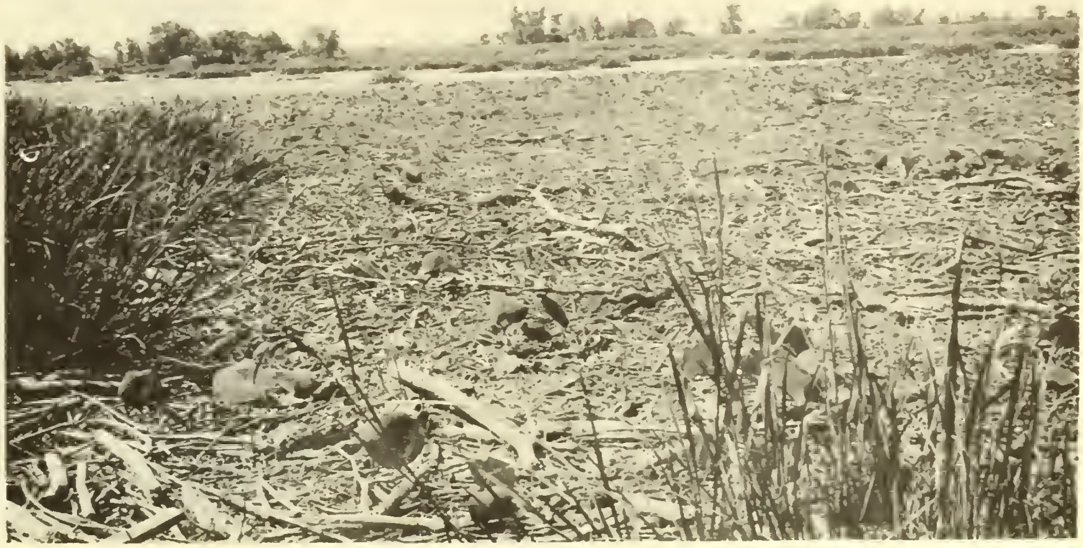


Fig. 10 Vegetal debris in North Bosque arm of Lake Waco

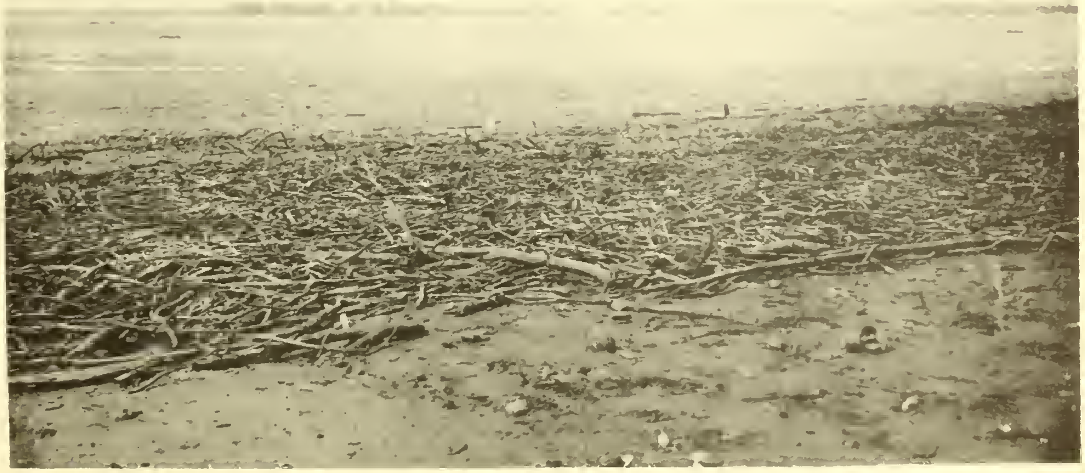


Fig. 11 Vegetal debris and sediment bars in North Bosque arm of Lake Waco. Water level 6 feet below crest.

UNITED STATES
DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

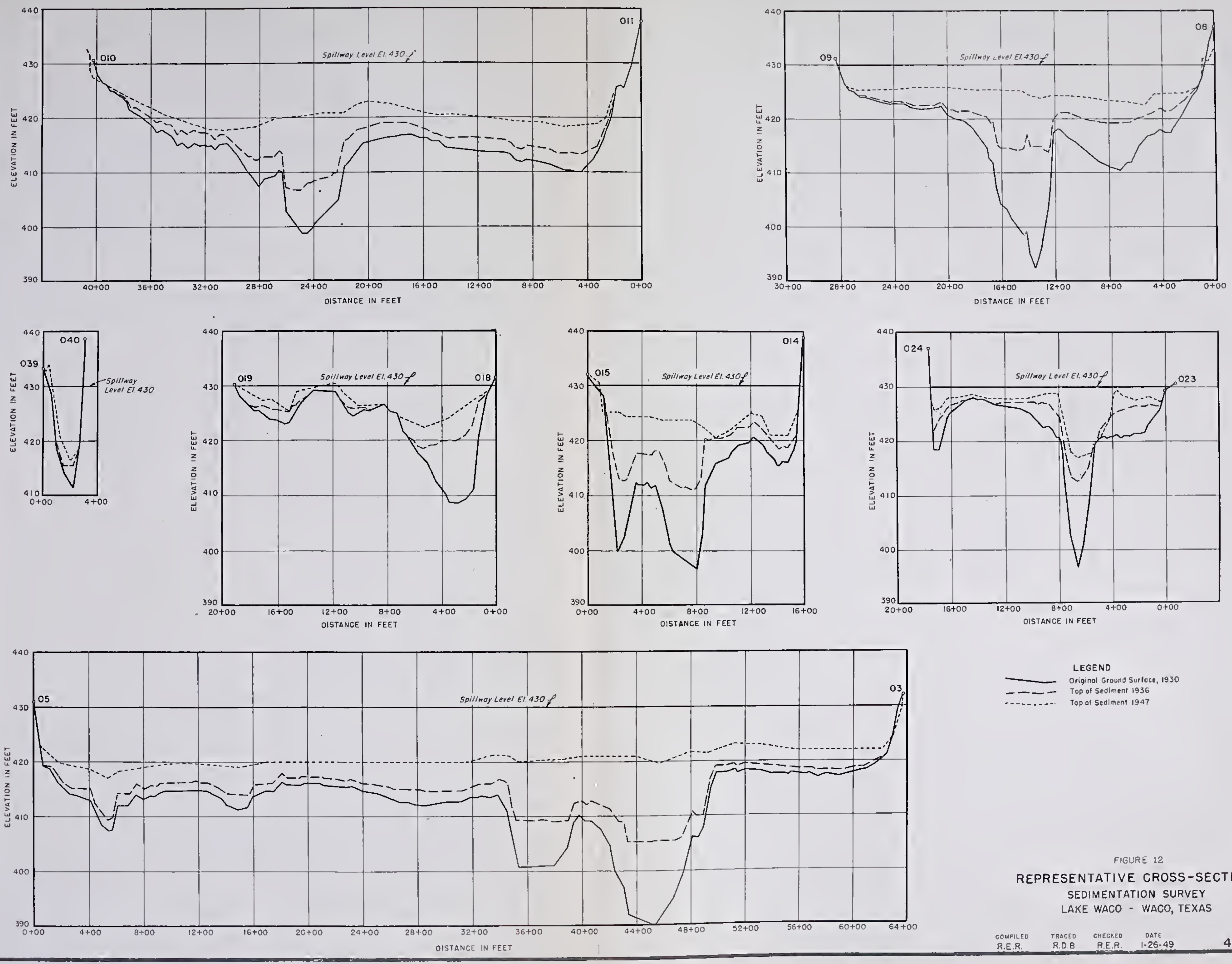


FIGURE 12

REPRESENTATIVE CROSS-SECTIONS

SEDIMENTATION SURVEY
LAKE WACO - WACO, TEXAS

COMPILED	TRACED	CHECKED	DATE
R.E.R.	R.D.B	R.E.R.	1-26-49

4-R-7109

AGR-SCS-FT WORTH,TEX SEPTEMBER,1952

UNITED STATES
DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

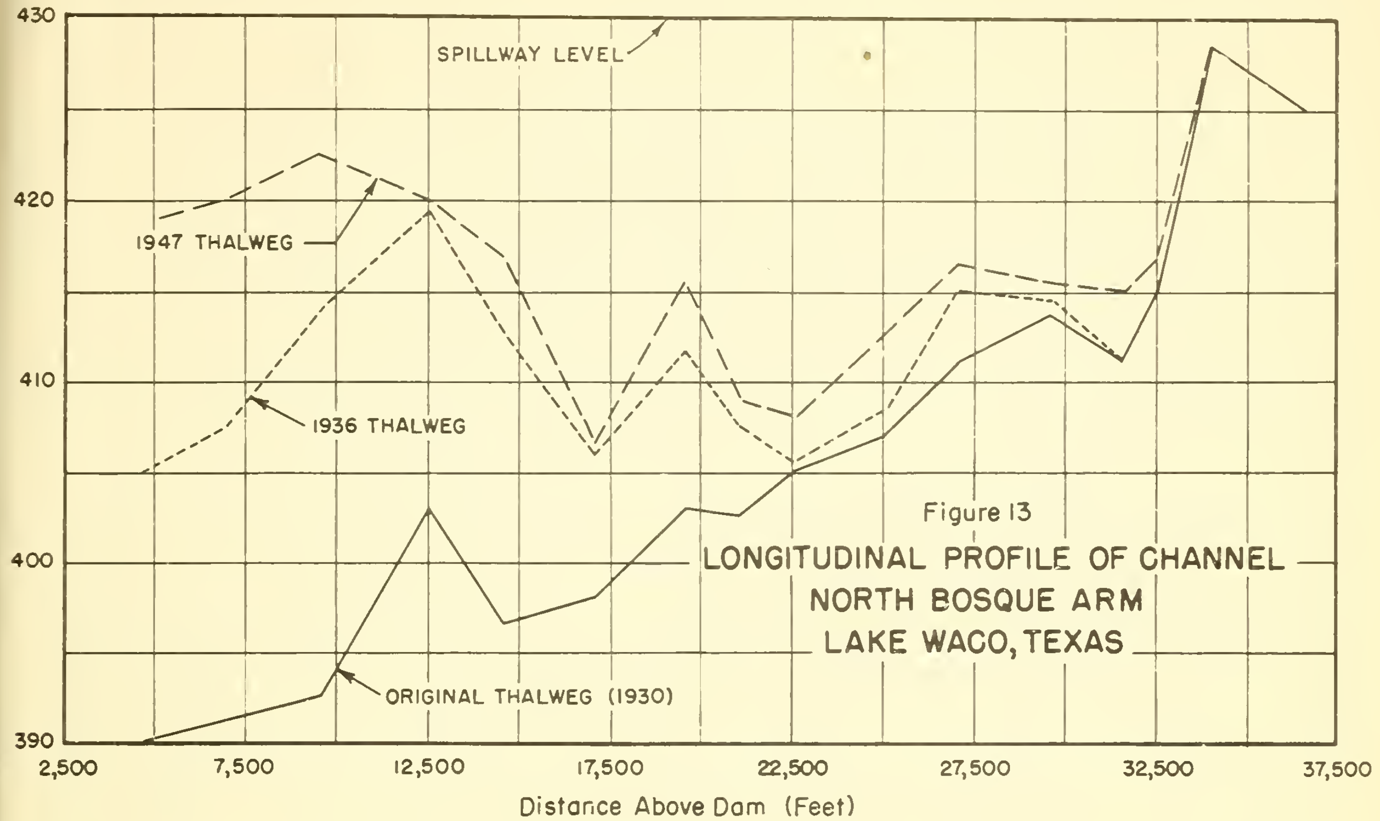


Figure 13

LONGITUDINAL PROFILE OF CHANNEL
NORTH BOSQUE ARM
LAKE WACO, TEXAS

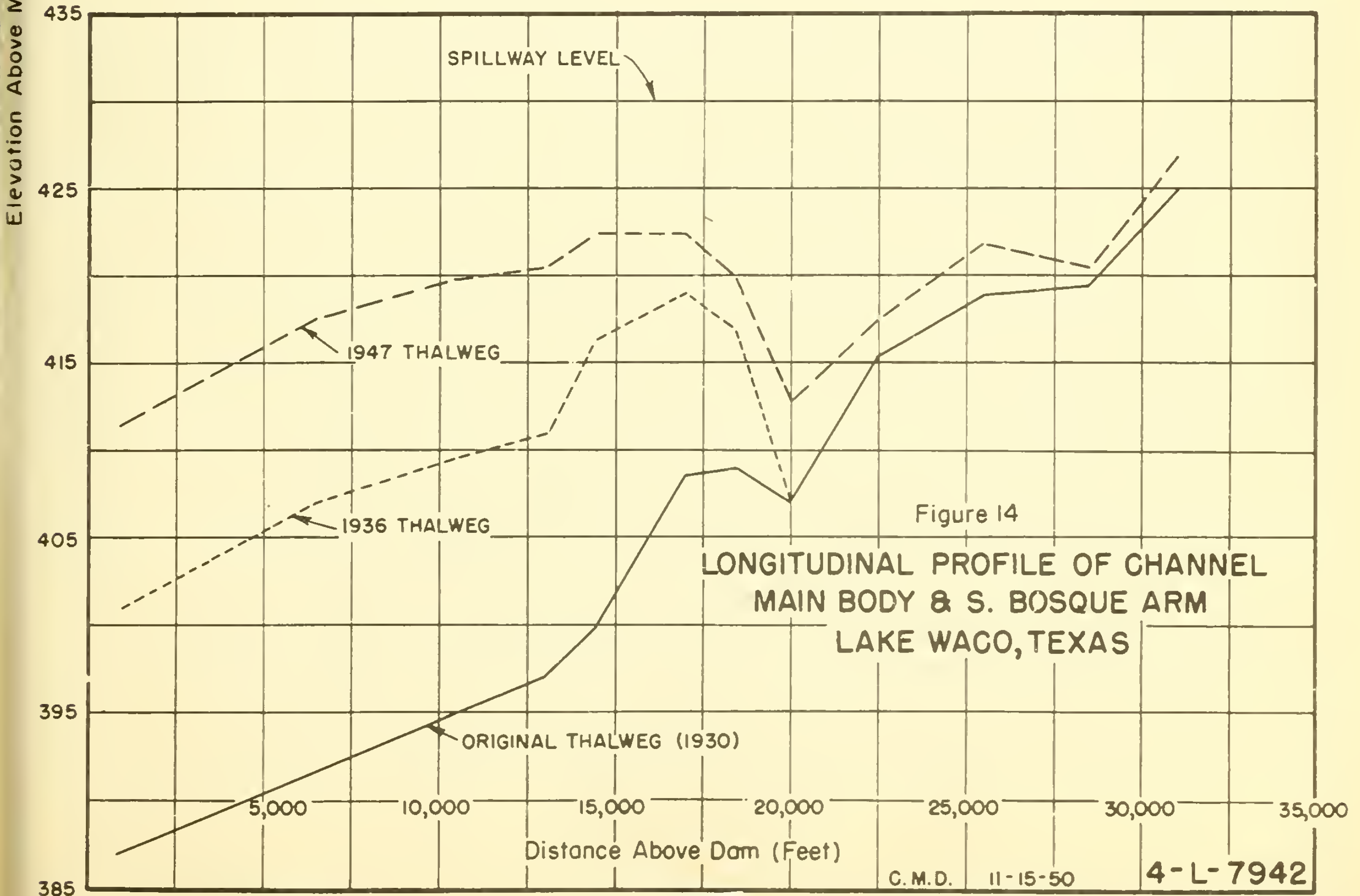


Figure 14

LONGITUDINAL PROFILE OF CHANNEL
MAIN BODY & S. BOSQUE ARM
LAKE WACO, TEXAS

AGR-SCS-FT WORTH, TEX AUGUST, 1952

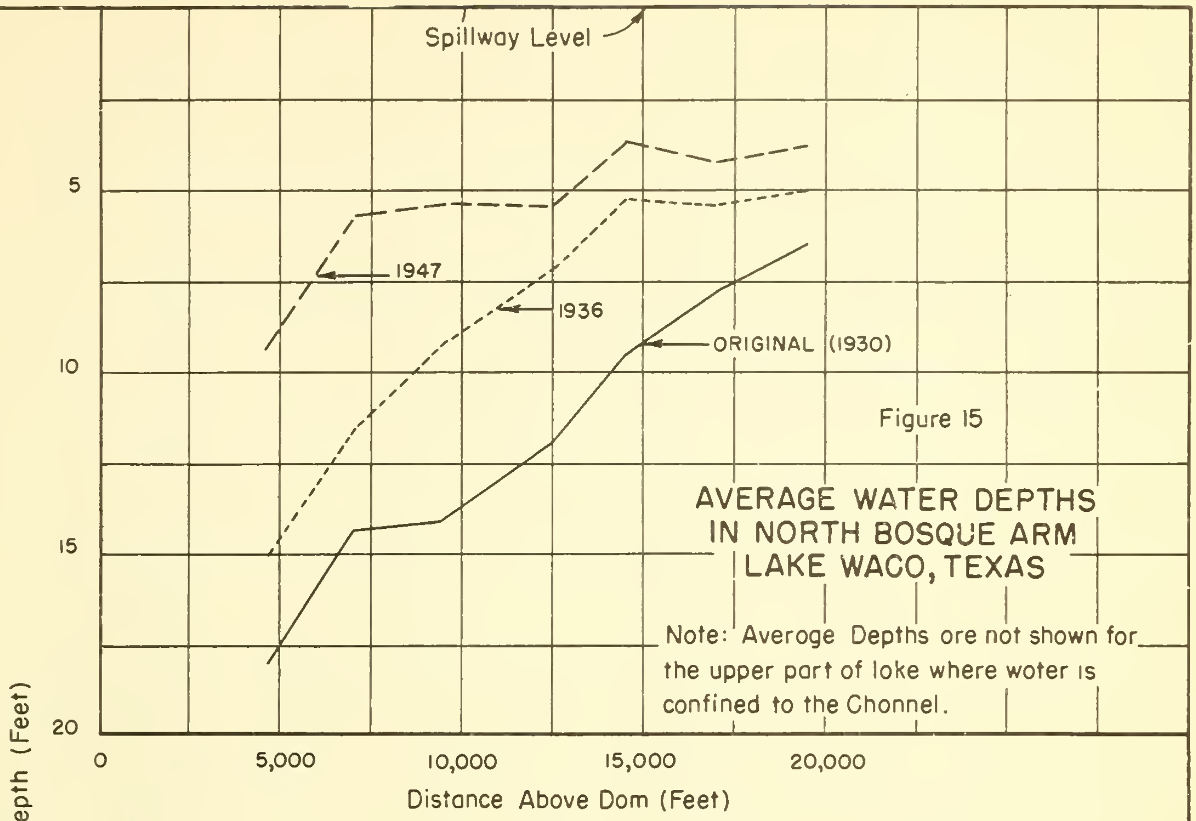


Figure 15

AVERAGE WATER DEPTHS IN NORTH BOSQUE ARM LAKE WACO, TEXAS

Note: Average Depths are not shown for the upper part of lake where water is confined to the Channel.

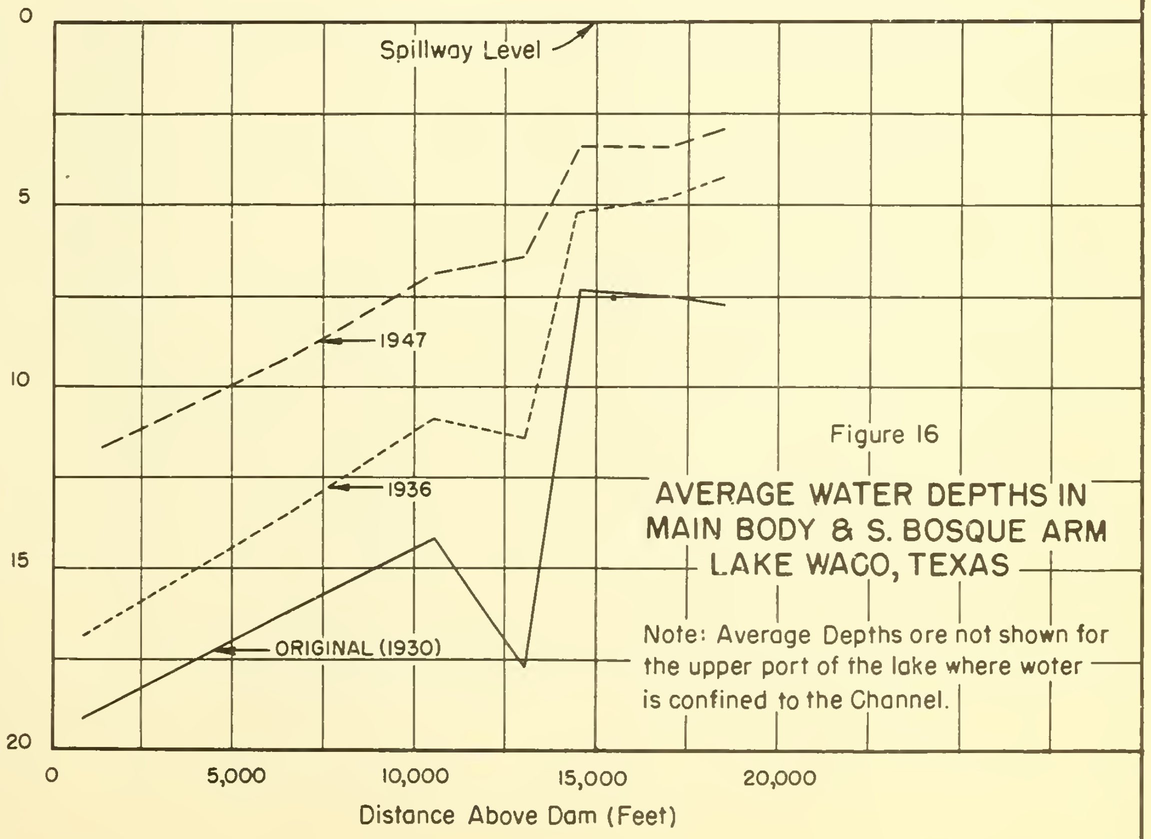


Figure 16

AVERAGE WATER DEPTHS IN MAIN BODY & S. BOSQUE ARM LAKE WACO, TEXAS

Note: Average Depths are not shown for the upper part of the lake where water is confined to the Channel.

C.M.D. 11-15-50 4-L-7943

Table 8 - Distribution of Storage Capacity and Sediment in Lake Waco

SECTION	AREA		PROPORTION OF TOTAL		CAPACITY[1/]						SEDIMENT[2/]			
					Original	Proportion of Original	Feb. 1936	Dec. 1947	Reduction				Proportion of Total Sediment	
	Acres	Acres	Percent	Percent	Ac.-ft.	Percent	Ac.-ft.	Ac.-ft.	Percent	Percent	Ac.-ft.	Ac.-ft.	Percent	Percent
	1936	1947							To 1936	To 1947	1936	1947	1936	1947
Main Basin Segments 1,2, and 3	1.150	1,150	41.1	41.9	20,608	52.3	17,650	12,413	14.4	39.8	2,958	8.195	38.0	47.2
Lower North Bosque Arm Segments 4,5, and 6	506	506	18.1	18.5	6,285	16.0	4,327	2,517	31.2	60.0	1,958	3,768	25.1	21.7
Middle North Bosque Arm Segments 7.8A, 8B, 36A,36B, 35,9, and 10	214	200	7.6	7.3	1,668	4.2	1.206	1,041	27.7	37.6	462	627	5.9	3.6
Upper North Bosque Arm Segments 11,12,13,14,15,16, 17,18, and 19	62	60	2.2	2.2	482	1.2	441	399	8.5	17.2	41	83	0.5	0.5
Lower South Bosque Arm Segments 20,21,22,37, and 23	481	474	17.2	17.3	6.854	17.4	5,471	4,179	20.2	39.0	1,383	2,675	17.8	15.4
Middle South Bosque Arm Segments 24,25,26,27, and 28	336	301	12.0	11.0	3,117	7.9	2,130	1,155	31.7	62.9	987	1,962	12.7	11.3
Upper South Bosque Arm Segments 28.29,30,31,32.33. and 34	52	51	1.9	1.9	364	0.9	363	322	0.3	11.5	1	42	0.0	0.2
Total North Bosque Arm	782	766	27.9	27.9	8,435	21.4	5,974	3,957	29.2	53.1	2.461	4,478	31.6	25.8
Total South Bosque Arm	869	826	31.0	30.1	10,335	26.2	7,964	5,656	22.9	45.3	2,371	4,679	30.4	27.0

[1/] Capacity figures include 326 acre-feet of water in channels of North and South Bosque arms which is partially impounded by sediment bars and not readily available for use.

[2/] Sediment figures do not include 54 acre-feet of above crest sediment measured in 1947.

UNITED STATES
DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

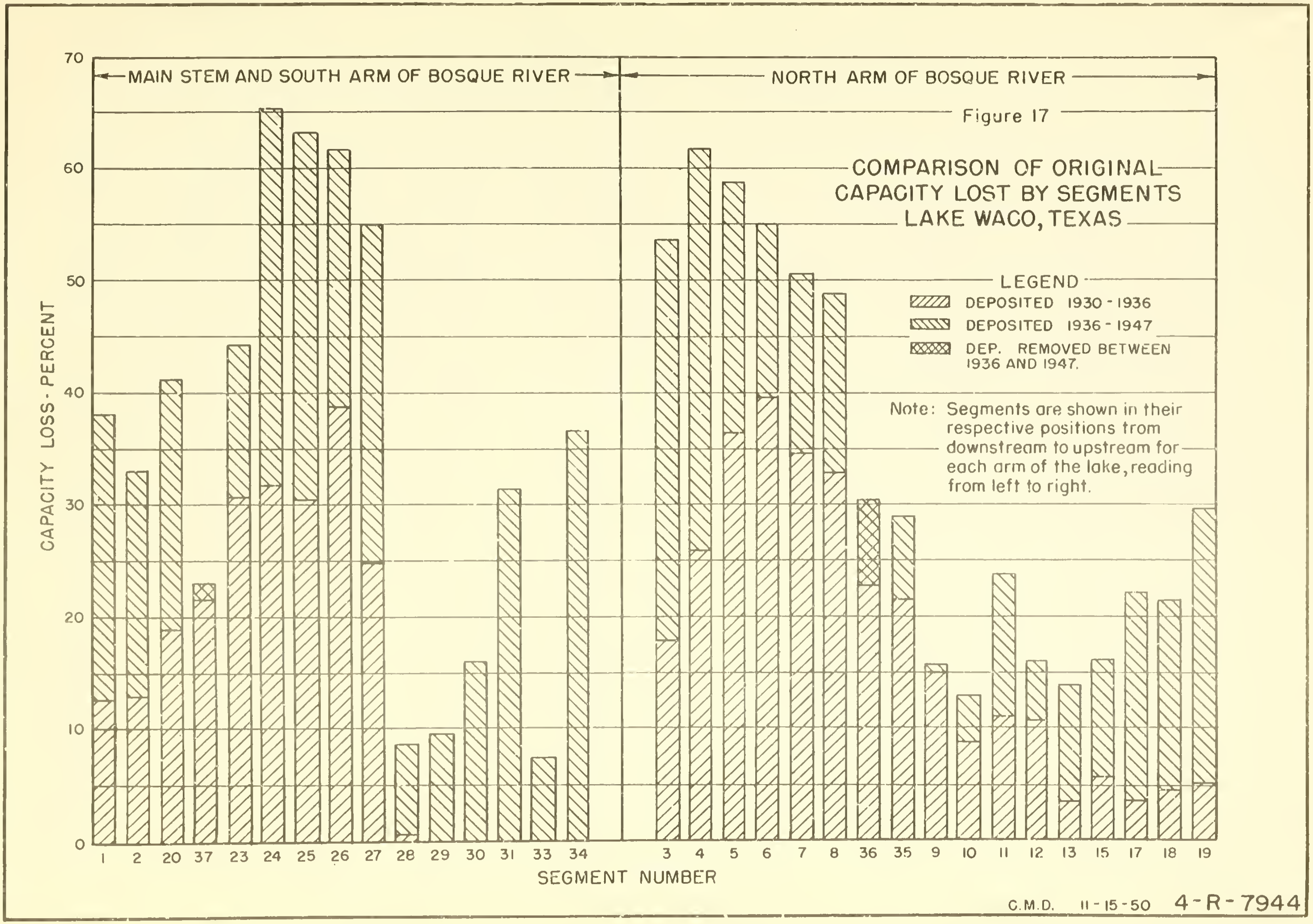


Figure 17

COMPARISON OF ORIGINAL CAPACITY LOST BY SEGMENTS LAKE WACO, TEXAS

Note: Segments are shown in their respective positions from downstream to upstream for each arm of the lake, reading from left to right.

AGR-SCS-FT WORTH,TEX SEPTEMBER,1952

by 1947. The lower part of the North Bosque arm, segments 4, 5 and 6, and the middle South Bosque arm, segments 24, 25, 26, 27 and 38, have sustained 60 and 62.9 percent capacity loss respectively to December 1947. In these areas the elevation of the top of sediment at the channel is higher in places than on adjacent flats, resembling submerged natural levees. At the Highway 67 bridge, segment 37, the channel is completely filled, and flood currents now maintain a flat-bottomed, nearly rectangular, section with a 10-foot water depth.

Figure 18 shows the distribution of sediment in relation to lake elevation. To obtain these curves the percent of total sediment below each contour in 1936 and 1947 was plotted against the contour elevation in feet. The volume of sediment within contour intervals is shown in figure 18. The lower third of the reservoir (elevation 402-387) was practically filled with sediment when the 1936 survey was made (table 5). At the time of the 1947 survey, 47 percent of the sediment had been deposited in the upper third of the reservoir (elevation 430-416). The middle third (elevation 416-402) contained 44 percent of the sediment in 1947, and had lost 90 percent of its original capacity. Obviously most of the sediment deposited in the lake in the future must be laid down in the upper third of the reservoir's depth or above crest. (figure 19).

Some deposition of sediment above crest level has occurred in the form of islands and narrow strips along shores in segments 26 and 27 of the South Bosque arm, and segments 8, 9, 10, 35 and 36 of the North Bosque arm. These areas also are shallow, marshy, and filled with water plants. The channels are temporary, as alternate scour and fill occurs. Since these parts of the lake are more than 50 percent filled with sediment, their future rate of capacity loss will be somewhat less than heretofore.

The narrow, ponded, channel segments 28-34 in the South Bosque arm and 11-19 in the North Bosque arm have sustained total reductions of 11.5 percent and 17.2 percent capacity loss respectively. These channels are subject to alternate scour and fill.

Irregularities in sediment deposition have resulted in the formation of bars across both main arms of the lake. In the North Bosque arm the bar is in the vicinity of Range 08-09, and in the South Bosque arm it is near Range 064-065. If the lake were drawn down to elevation 422 feet or below, the total volume of water impounded behind the bars would be about 326 acre-feet (December 1947), and would not be available for use without ditching. This volume, however, was not deducted in computing 1947 capacity of the reservoir.

Future Trends of Sedimentation in the Reservoir

On the basis of present data, a lower rate of sedimentation is predicted for Lake Waco for the period 1948-1957 than for any previous period in

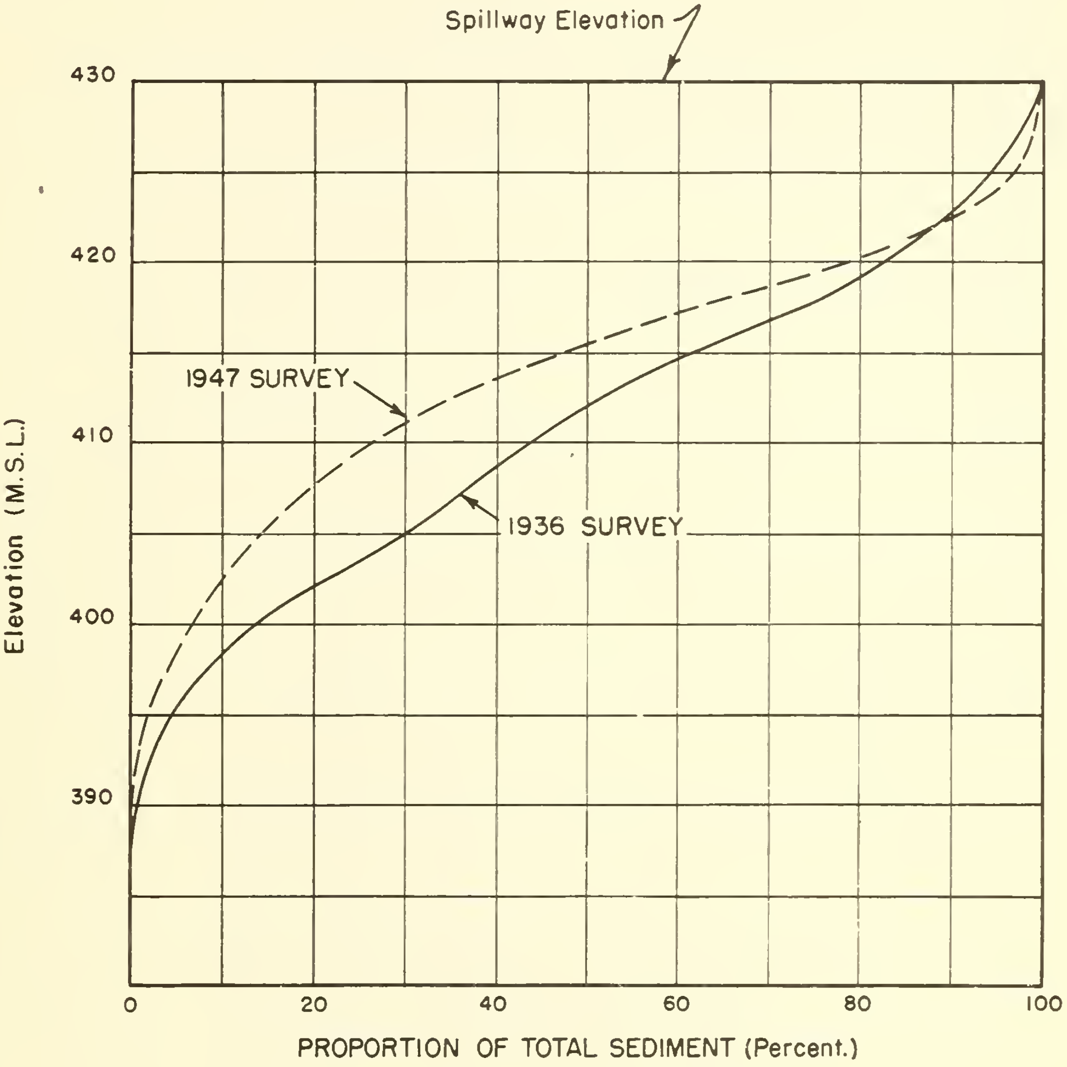


Figure 18

VERTICAL DISTRIBUTION OF SEDIMENT
LAKE WACO, TEXAS

C.M.D. 11-15-50 **4-L-7941**

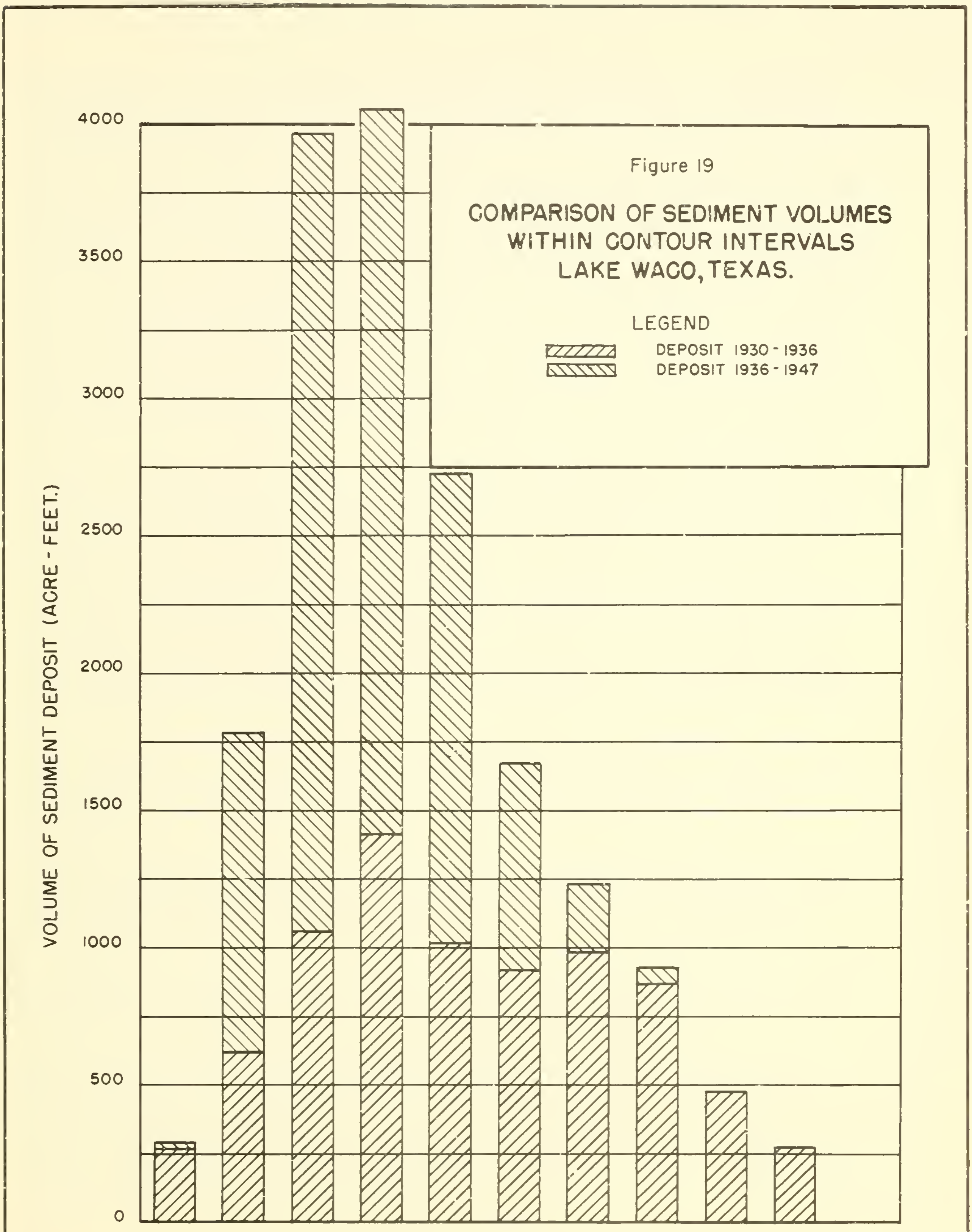


Figure 19

COMPARISON OF SEDIMENT VOLUMES WITHIN CONTOUR INTERVALS LAKE WACO, TEXAS.

AGR-SCS-FT WORTH,TEX. SEPTEMBER, 1952

the history of the reservoir. The trends in land use and farming practices, the continuing development of erosion controls which have already been installed on about 10 percent of the area, the probable effect of an upland flood-control program, and the stage of sedimentation in the reservoir are all influences which tend to reduce the future rate of capacity loss. As shown in table 6, the annual rate of loss from 1930 to 1936 was 3.35 percent; from 1936 to 1947 it was 2.06 percent; and for the total life of the reservoir (1930 to 1947) it was 2.49 percent. As the reservoir reaches a more advanced stage of sedimentation, more sediment will be carried through the spillway. Therefore it is predicted that the annual rate of capacity loss for the next 10 years will be on the order of 12.5 percent less than for the period 1936-1947. For the purpose of uniformity in calculation, the figure 1.8 percent (annual capacity loss) is used in estimating future effects of sedimentation upon the municipal water supply.

Irregularities of sediment deposition within the lake basin may require some changes from the present program of operation and maintenance. As the broad sediment bars, previously described, near range 08-09 in the North Bosque arm and range 064-065 in the South Bosque are built higher, the water in upstream areas above them will be impounded at higher levels in case the reservoir is drawn down. It is predicted that the resulting volume of unavailable storage will increase from the present figure of 326 acre-feet to about 600 acre-feet some time within the next 5 to 10 years. Soon thereafter the rapid deposition of sediment in both arms will fill the lower areas, and the remaining storage capacity in these areas will be negligible.

The submerged channels in the broad part of the reservoir, segments 1, 2, 3 and 20, are already completely filled with sediment and future deposition will occur more or less uniformly in all 4 segments.

Rapid decreases in water area will occur as more sediment is deposited near crest level in segments 6, 7, 8, 9, 10, 35 and 36 of the North Bosque arm and segments 24, 25, 26 and 28 of the South Bosque arm.

The ponded channels above ranges 039-040 and 056-057 will not suffer substantial decreases in capacity in the near future.

Some increase in average specific weight of the reservoir deposit will occur as more sediment is deposited at and near crest, and as the thick sediment receives the weight of new deposits. The average weight per cubic foot, now 58.5 to 60 pounds, however, is not expected to exceed 63 pounds in the next 10 years unless the water is drawn down to low levels for long periods.

PRECIPITATION AND RUNOFF

Precipitation

The average annual rainfall in the Lake Waco drainage area ranges from 30 inches near Stephenville, in the headwaters of the North Bosque River, to 35 inches near Waco (10). Precipitation normally is more abundant during the spring and fall seasons, and occasional short periods of drought occur during the summer season. The extremes in annual rainfall at Waco range from a minimum of 13 inches to a maximum of 52 inches. Occasional heavy rain storms cause high stream flows which carry most of the sediment into Lake Waco. Storms producing as much as 6 inches of rainfall in one day over substantial areas in the Bosque River Basin have occurred. Storms producing 4 to 8 inches precipitation during a 2- to 4-day period are not unusual.

Total Water Flow

Available stream-gage records provide only fragmentary data on stream flow into the reservoir. Furthermore, accurate records of outflow through Lake Waco spillway are not available. Estimates of annual outflow through Lake Waco were made, however, to provide a basis for estimating the amount of sediment carried past the spillway (table 11). The average annual outflow for the period March 1936 to December 1947 was found to be 32 percent greater than for the period April 1930 to February 1936. Although the volumes of inflow and outflow are not the same they are directly related, so the inflow to Lake Waco was considerably higher during the second period than during the first.

High and Low Flows

Studies of turbidity records of the city filter plant show that high rates of flow usually transport a greater amount of sediment per unit of volume of water than low rates of flow. In order to determine whether the higher rate of sedimentation occurring in Lake Waco during the period 1930-1936 might have been caused by a greater number of high inflows, an analysis was made of the frequency of such flows during the life of the lake. This study was based on the daily flow records at the Clifton gage. A count was made of the number of days that the mean flow exceeded 1,000 second-feet for each of the periods, and further extended by counting the number of days in which the mean flow fell within increments of 1,000 second-feet in excess of the minimum 1,000 second-feet tabulated. The average number of days per year in which flow exceeded the increments thus counted was then computed for the periods Oct. 1930-Jan. 1936 and Feb. 1936-Sept. 1945. The results are summarized in figure 20.

The frequency of occurrence of high discharges has been greater during the second period than during the first period in all cases. Likewise the average annual inflow was higher for the second period.

UNITED STATES
DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

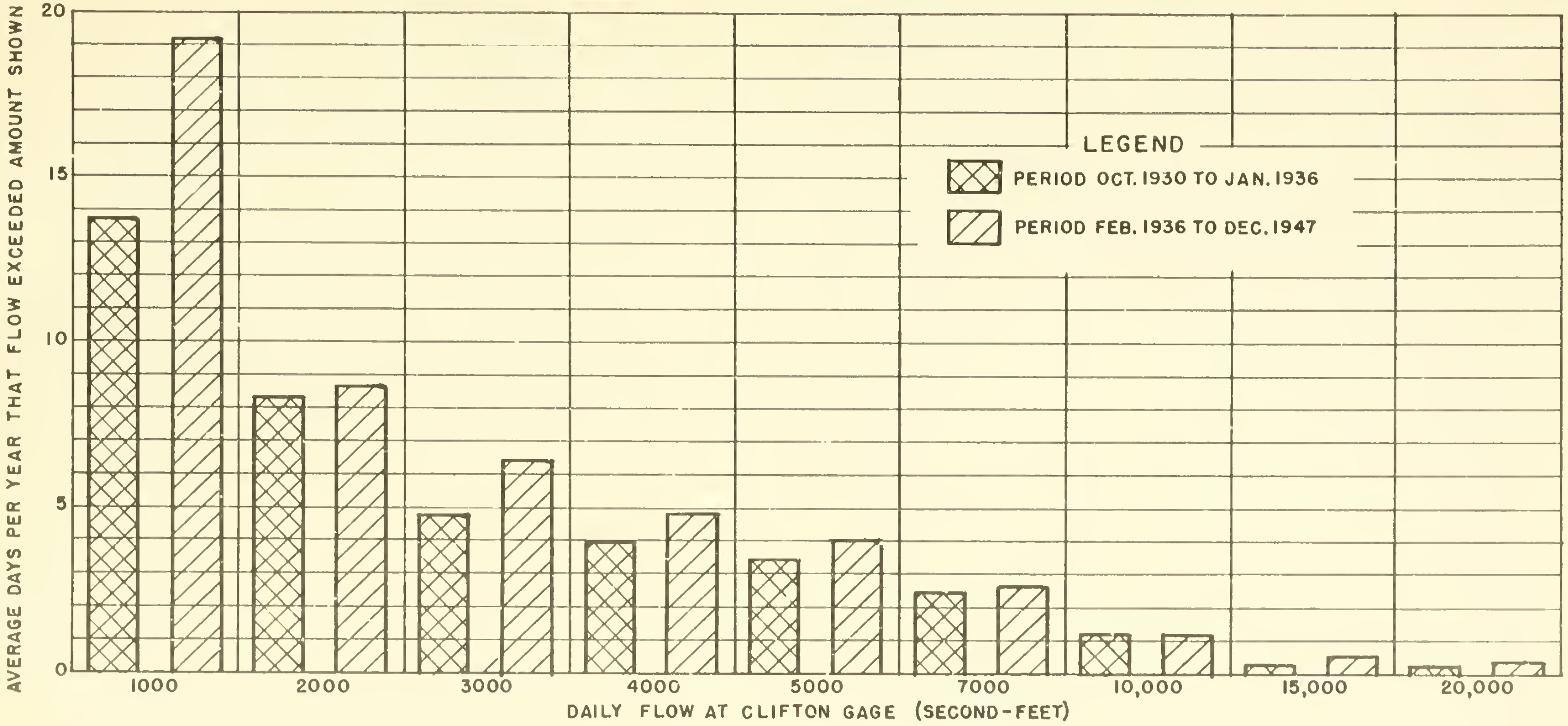


FIGURE 20

COMPARISON OF HIGH FLOWS ON NORTH BOSQUE RIVER

BOSQUE COUNTY

TEXAS

SOURCE:
U.S.G.S. RECORDS AT CLIFTON GAGE

COMPILED	TRACED	CHECKED	DATE
R.E.R.	P.E.M.		1-21-49

4-L-7099

Therefore the decrease in the rate of sedimentation during the second period must be due to factors other than the difference in volume of flow or the frequency of high flows.

Periods of low flow, when water entering the lake is less than the amount being used by the city and being lost in other ways, will ultimately cause a water shortage providing they are of sufficient duration. Sediment in the lake, by occupying space in which water would otherwise be stored, decreases the water supply available for use during these periods of low flow. The continued accumulation of sediment and probable increase in water requirements of the city each year cause a yearly decrease in the length of period of low flow which the city could experience and still continue to use water from the lake at a normal rate.

Analysis of the stream-flow records for the Bosque River show that there have been two periods since 1923 of more than six consecutive months when the total flow has been materially less than the present water use. Table 9 shows the estimated monthly flow into Lake Waco for these periods. The period August, 1924 to April, 1925, 9 months in duration, has one month when inflow exceeds the expected water use. The period August, 1939 to March 1940 has considerably less flow but is only 8 months long. The total flow for the first period exceeds the second period by 2,842 acre-feet, an amount nearly three times the present monthly water use, so the greater deficiency in flow occurred during the second period.

Table 9 - Monthly discharge of Bosque River at Lake waco during periods of low flow.

Date	Amount 1/ (Acre-feet)	Date	Amount 2/ (Acre-feet)
July 1924	1,209	Aug. 1939	538
Aug. 1924	268	Sept. 1939	32
Sept. 1924	467	Oct. 1939	76
Oct. 1924	325	Nov. 1939	492
Nov. 1924	1,672	Dec. 1939	474
Dec. 1924	715	Jan. 1940	312
Jan. 1925	747	Feb. 1940	336
Feb. 1925	586	Mar. 1940	194
Mar. 1925	365	Apr. 1940	13,160
Apr. 1925	151		
May 1925	16,496		

1/ Computed by multiplying recorded flow at Speegleville by factor 1.05 and multiplying recorded flow at Clifton by 1.39, and adding the two together.

2/ Computed by multiplying recorded flow at Clifton gage by the factor 2.00.

TOTAL SEDIMENT LOAD IN THE BOSQUE RIVER SYSTEM

Basis for Estimates

No program of suspended sediment sampling in conjunction with stream gaging has yet been developed in the Bosque River Basin. The city filter plant, however, has made visual turbidity readings, at the rate of one to three per day, on lake water entering the plant since construction of the reservoir. These turbidity measurements have been recorded as parts per million by weight of total water treated for city use. Turbidity readings do not compare exactly with laboratory measurements of suspended sediment because of color differences, degree of floculation and other factors, but they are used here in conjunction with the survey data as a basis for estimating the total sediment load carried into Lake Waco including that transported past the dam.

Accurate records of reservoir water levels, gate openings and water flow past the spillway have not been maintained uniformly for Lake Waco, but the records for some periods are sufficiently complete to permit calculations of discharge from the reservoir in relation to rainfall in the drainage area. Therefore the rainfall records (10) from four well-distributed stations at McGregor, Clifton, Dublin and Hico (fig. 4) were used to calculate runoff caused by all storms of consequence (total 122) during the life of the reservoir. Individual hydrographs were prepared by E. F. Carmichael* for 17 storms of all magnitudes which occurred at dates when records on overflow from Lake Waco were available. Two curves were plotted showing the relationship between rainfall in the drainage area and overflow from the spillway - one for high runoff caused by storms of higher intensity, the other for lower runoff caused by storms of lower intensity. It was determined that storms causing less than 0.1 inch average runoff normally produced little or no overflow. On this basis the remaining storms (time and depth of precipitation) were plotted upon the curves, using weighted rainfall for the entire basin, and total flow over the spillway was obtained from the curves. It was found that base flow of the North and South Bosque Rivers between storm periods normally does not cause flow over the spillway. These methods were the only feasible means of estimating monthly, annual and total flow through Lake Waco.

To obtain estimates of sediment carried past Lake Waco spillway, the average turbidity of water entering the filter plant, in parts per million, was applied to the total flow from the reservoir during each storm period. Since the intake for city water is near the spillway, and the tower intake is not greatly different in elevation from the gate openings, it is believed that a reasonable estimate of total sediment

---

*Hydrologist, Water Conservation Division, Soil Conservation Service, Fort Worth, Texas

was obtained. Also density currents in Lake Waco are probably negligible because most storms produce considerable turbulence and turbidity in the reservoir even near the dam. It was found that water pumped into the filter plant during quiet periods between storms generally contained from 40 to 60 parts per million suspended solids. During such periods, when water used by the city constitutes the only outflow from the reservoir, the amount of sediment carried past the dam is negligible. During periods of 3 to 4 months duration between rainstorms, usually less than 0.4 acre-foot of sediment enters the filter plant.

Table 10 shows a summary by years of total water flow and total sediment load at Lake Waco for the period April 1930 through December 1947. The data in table 10 are not comparable in accuracy to records based upon reliable stream gaging and suspended sediment sampling, but the authors believe that the proper relationships between sediment deposited in the reservoir, suspended sediment carried past the spillway, and conditions in the drainage area are shown. Sediment deposited in the reservoir is listed on an annual basis for the periods between surveys, and hence does not reflect the effect of variations in rainfall, and runoff, and drainage-area conditions year by year. The deposit of one year's period (1935-36) was accurately measured, however, as the interval between the 1935 and 1936 surveys was approximately one year. It was a year of unusually high rainfall, however, and therefore not typical. All figures on sediment quantity in the table are in acre-feet on the basis of 58.5 pounds per cubic foot, the average dry weight of the samples taken in 1947. This figure may be slightly low because existing equipment prevented sampling the deeper sediment in the thickest parts of the deposit.

Total Sediment Deposits and Suspended Sediment

Comparison of the two periods summarized in table 10 indicates the trends in sediment output from the drainage area since construction of Lake Waco. The summary shows that the average annual number of storms causing flow over the spillway was 7 during the period 1930 to 1936 and 9 during the period 1936 to 1947. The average annual water discharge during the first period was 374,000 acre-feet and during the second period was 494,000 acre-feet (35 percent greater). Yet the quantity of sediment carried annually past the spillway was only 11 percent greater during the second period and the annual volume of the deposition in the reservoir basin was 39 percent less. According to this summary the average annual rate of sediment contribution from the drainage area was 1.0 acre-foot per square mile from 1930 to 1936 and 0.7 acre-foot from 1936 to 1947. The trap efficiency of the reservoir to the date of the 1947 survey was approximately 71 percent.

CAUSES OF THE HIGH RATES OF SEDIMENTATION

The chief cause of the high rate of capacity loss by sedimentation is the excessive size of the drainage area as compared to the original

Table 10. Summary of total sediment load
in the Bosque River System
June 1930 - December 1947

Year	No. of storms causing flow over spillway	Water flow from lake	Sediment carried past the dam	Sediment 2/ deposited in lake	Total sediment for year	Average annual output per sq.mi. of drainage
		Ac.ft.	Ac.ft. 1/	Ac.ft. 1/	Ac.ft. 1/	Ac.ft. 1/
1930 (Apr-Dec)	6	420,500	210	867	1077	
1931	3	55,000	7	1155	1162	
1932	9	517,000	194	1155	1349	
1933	7	336,200	181	1155	1336	
1934	7	265,500	238	1155	1393	
1935-36	12	612,800	897	2303	3200	
Summary Apr.'30-Feb'36	44	2,207,000	1727	Total 7790	9517	
Annual Averages	7	374,000	293	1320	1613	1.0
1936 (Mar-Dec)	6	655,000	380	652	1032	
1937	10	412,400	127	810	937	
1938	6	327,600	137	810	947	
1939	5	277,400	194	810	1004	
1940	9	445,000	455	810	1265	
1941	11	703,100	402	810	1212	
1942	11	824,150	563	810	1373	
1943	5	91,200	5	810	815	
1944	11	582,400	687	810	1497	
1945	11	523,700	266	810	1076	
1946 3/	8	494,000	327	810	1137	
1947 3/	9	494,000	327	810	1137	
Summary 1936-47	102	5,830,000	3870	Totals 9562	13,432	
Annual Averages	9	494,000	328	810	1,138	0.7

1/ On the basis of 58.5 lbs. per cubic foot as determined from 9 samples in 1947.

2/ Annual averages between surveys.

3/ Hydrologic data not available. Sediment carried past dam is an average of the rate for the period 1936-45.

capacity of the reservoir (23.6 acre-feet per square mile, see table 6). Thus the average annual volume of water flowing through the reservoir is many times that necessary to provide adequate water supply, and sediment eroded from the excessively large drainage area is causing a high rate of capacity loss.

Furthermore, on the basis of soil erosion surveys made by the Soil Conservation Service, it is estimated that about 80 percent of the sediment contributed to the reservoir originates in 800 square miles of the drainage area (about 50 percent) which lies nearest to the reservoir. This area includes all of the highest sediment producing areas, namely the cultivated Grand Prairie and the Black Prairie, except the West Cross Timbers.

WATER CONSUMPTION FROM LAKE WACO

Past History

In 1931, when water from Lake Waco was first used for the entire year, a total of 1,409 million gallons were pumped to the city for all uses. Until 1936, yearly water use fluctuated above and below this amount, with no trend toward an increase. Water use increased sharply in 1936 and again in 1937, when 1,829 million gallons were used, followed by another period of several years when water use remained about the same. In 1942, the first full year of World War II, water use increased sharply, and this rate of increase has continued with no evidence of slacking off through 1948. In 1946, Waco used 2,620 million gallons of water, nearly double the amount required in 1931. Figure 21 shows the amount of water pumped to the city by months from June, 1930 to December, 1948. These data are also presented in table 11 with monthly and annual increases in water pumped for the over-all period of record and for the period 1941-1948. The average annual increase in water pumped from 1931 to 1948 has been 360.9 acre-feet compared to an annual increase of 740.7 acre-feet from 1941 to 1948.

Future Use

It seems likely that industrial expansion and increases in population will continue in Waco at a relatively high rate while the present economic conditions prevail. In case of an economic depression industrial and domestic use would probably decline. If full-scale war should develop, the increase in water use could easily be greater than that which occurred from 1941 to 1948. Since the occurrence of either a depression or another full-scale war is speculative, it is estimated that normal substantial growth of business, industry and population will occur.

The maximum rather than the minimum probable water needs of Waco should be assured if its industrial and residential growth is to be

UNITED STATES
DEPARTMENT OF AGRICULTURE

SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

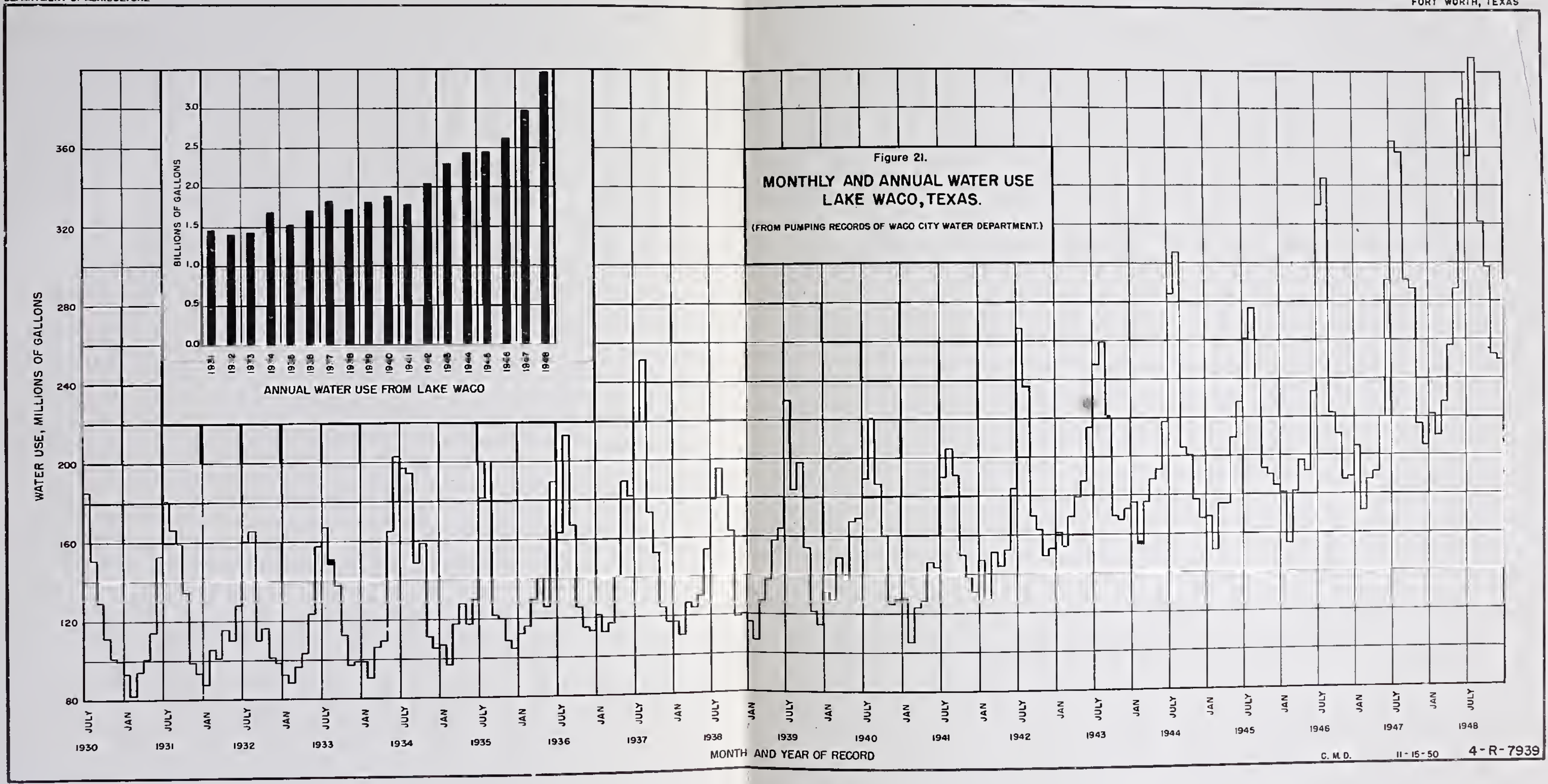


Figure 21.

MONTHLY AND ANNUAL WATER USE LAKE WACO, TEXAS.

(FROM PUMPING RECORDS OF WACO CITY WATER DEPARTMENT.)

AGR-SCS-FT WORTH,TEX SEPTEMBER,1952

Table 11 - Water Pumped to City from Lake Waco

Thousands of Gallons

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1930						99,202	185,391	152,587	129,070	111,407	100,466	99,625	
1931	92,954	82,089	94,126	100,578	113,915	152,587	181,318	165,950	158,599	133,905	99,145	93,608	1,468,774
1932	87,677	105,631	100,842	115,619	109,967	128,086	160,066	165,415	109,790	115,896	101,372	98,790	1,405,151
1933	92,250	88,649	96,597	102,907	123,429	157,480	166,885	148,322	137,206	112,406	97,094	99,137	1,422,362
1934	98,819	90,611	105,937	109,105	164,729	202,915	196,934	194,256	148,501	158,363	111,508	105,275	1,686,952
1935	107,073	96,413	117,833	128,129	117,610	129,711	181,532	200,569	121,898	120,285	109,050	104,878	1,534,982
1936	112,683	116,526	129,426	139,821	125,996	189,358	163,452	212,888	167,504	125,684	115,284	113,816	1,712,438
1937	121,156	112,114	117,093	140,912	188,765	181,811	219,704	251,293	173,163	152,390	124,058	116,819	1,829,278
1938	117,264	109,980	126,669	124,214	129,849	153,876	179,333	195,105	181,111	162,742	118,733	120,310	1,719,186
1939	116.037	106,792	126,599	137,637	157,907	164,321	229,876	184,287	197,916	154,376	121,536	115,133	1,812,417
1940	131,285	127,180	148,926	137,366	167,766	169,346	189,476	220,952	186,551	161,058	124,985	126,941	1,891,832
1941	127,516	105,720	123,371	126,370	146,410	143,727	190,170	204,500	190,826	150,180	138,417	131,170	1,778,377
1942	147,027	127,820	151,680	144,098	152,697	184,020	266,317	236,150	169,817	162,470	149,457	152,790	2,044,343
1943	161,083	153,240	169,680	179,530	187,745	215,240	247,790	259,050	221,710	169,580	167,400	173,170	2,305,218
1944	176,510	155,980	176,410	188,070	193,210	217,550	283,840	304,870	204,310	200,590	177,600	168,220	2,447,160
1945	168,320	150,950	174,950	174,940	208,800	227,860	260,230	275,940	239,020	193,232	190,100	184,436	2,448,778
1946	180,430	154,500	181,250	197,200	191,890	232,530	329,820	343,510	221,730	211,230	186,960	188,720	2,619,770
1947	204,740	171,570	187,540	191,320	218,740	290,480	362,810	357,660	290,450	286,067	216,140	205,020	2,982,537
1948	220,800	209,950	227,450	256,550	285,920	350,000[1]	390,410[1]	406,970	320,950	297,680	252,000	249,300	3,467,980
Average Annual Increase in Water Use from 1931 to 1948 (Thousands of gallons, by months)													
	7,520	7,521	7,843	9,175	10,118	11,612	12,300	14,178	9,550	9,634	8,991	9,158	117,600
Average Annual Increase in Water Use from 1931 to 1948 (Acre-Feet)													
	23.08	23.08	24.07	28.16	31.05	35.64	37.75	43.51	29.31	29.57	27.59	28.10	360.90
Average Annual Increase in Water Use from 1941 to 1948 (Acre-Feet)													
	40.90	45.70	45.63	57.07	61.16	90.43	87.79	88.77	57.05	64.67	49.80	51.79	740.75

[1] Adjusted use for June and July, 1948 substituted for actual use to conform with normal relationship of amounts used for these months. Total adjusted use for the 2 months equal total actual use.

1 ac.-ft. = 325,850 gal.

unhampered. Thus the larger increase in water use from 1941 to 1948 (740.7 acre-feet per year) was anticipated. This increase should be sufficient to allow for the city's normal growth. Estimates of monthly and annual water use to 1958 are shown in table 12.

EFFECTS OF SEDIMENTATION ON FUTURE WATER ECONOMY

Basis of Analysis

One of the objectives of this investigation has been to determine the future date at which the increase in the city's water requirements and the decrease in reservoir capacity by sedimentation would require the impoundment of additional water. In making this estimate the following assumptions were made:

1. The annual rate of capacity loss in Lake Waco, in the future, due to sedimentation will be 1.8 percent or 689 acre-feet. This reduction in future rate as compared to the average is explained in an earlier paragraph under "Future Trends of Sedimentation in the Reservoir."

2. The annual and monthly use of water from Lake Waco will be as shown in table 12.

3. The amount of water ponded behind sediment bars and not readily available for use by the city will increase. The 1947 survey showed 326 acre-feet of water was then blocked off by sediment bars, an amount equivalent to 18 acre-feet per year since water storage began in 1930. Since little or no ponding should have occurred during the early life of the reservoir it is estimated that the future loss from ponding will be higher than the 1947 average, or about 30 acre-feet per year.

4. A period of deficient stream flow at least equal to the greatest recorded deficiency and occurring at the same time of year (see table 9) might be experienced at any future date. The total flow into Lake Waco for the period of greatest recorded deficiency, from August, 1939 to March 1940, was 2,454 acre-feet.

5. Evaporation from the lake's surface amounts to several inches each month. The nearest place where usable evaporation data are readily available is the Blackland Conservation Experiment Station at Temple, Texas, about 35 miles southwest of Lake Waco. At this station records of evaporation from a free water surface have been obtained since 1915. They show the average evaporation from 1915 to 1941 to be 59.65 inches annually (6). The average evaporation for the 8-month period - August to March - amounted to 32.63 inches.

Evaporation is usually measured from a circular land pan 6 feet in diameter and 2 feet deep which is partially sunk into the ground. It is commonly accepted that land pans have a higher annual rate of evaporation

Table 12 - Estimated Future Water Use from Lake Waco[1]

Year	Jan. Ac.-Ft.	Feb. Ac.-Ft.	Mar. Ac.-Ft.	Apr. Ac.-Ft.	May Ac.-Ft.	June Ac.-Ft.	July Ac.-Ft.	Aug. Ac.-Ft.	Sept. Ac.-Ft.	Oct. Ac.-Ft.	Nov. Ac.-Ft.	Dec. Ac.-Ft.	Total Ac.-Ft.
1948[2]	677.61	644.31	698,02	787.33	877.46	1,074.11	1,198.13	1,248.95	984.96	913.55	773.36	765.08	10,642.87
1949	718.51	690.01	743.65	844.40	938.62	1,164.54	1,285.92	1,337.72	1,042.01	978.22	823.16	816.87	11,383.63
1950	759.41	735.71	789.28	901.47	999.78	1,254.97	1,373.71	1,426.49	1,099.06	1,042.89	872.96	868.66	12,124.39
1951	800.31	781.41	834.91	958.54	1,060,94	1,345.40	1,461.50	1,515.26	1,156.11	1,107.56	922.76	920.45	12,865.15
1952	841.21	827.11	880.54	1,015.61	1,122.10	1,435.83	1,549.29	1,604.03	1,213.16	1,172.23	972.56	972.24	13,769.94
1953	882.11	872.81	926.17	1,072.68	1,183.06	1,526.26	1,637.08	1,692.80	1,270.21	1,236.90	1,022.36	1,024.03	14,346.47
1954	923.01	918.51	971.80	1,129.75	1,244.42	1,616.69	1,724.87	1,781.57	1,327.26	1,301.57	1,072.16	1,075.82	15,087.43
1955	963.91	964.21	1,017.43	1,186.82	1,305.58	1,707.12	1,822.66	1,870.34	1,384.31	1,366.24	1,121.96	1,127.61	15,838.19
1956	1,004.81	1,009.91	1,063.06	1,243.89	1,366.74	1,797.55	1,900.45	1,959.11	1,441.36	1,430.91	1,171.76	1,179.40	16,568.95
1957	1,045.71	1,055.61	1,108.69	1,300.96	1,427.90	1,887.98	1,988.24	2,047.88	1,498.41	1,495,58	1,221.56	1,231.19	17,309.71
1958	1,086.61	1,101.31	1,154.32	1,358.03	1,489.06	1,978.41	2,076.03	2,136.65	1,555.46	1,560.25	1,271.36	1,282.98	18,050.47
1959	1,127.51	1,147.01	1,199.95	1,415.10	1,550.22	2,068.84	2,163.82	2,225.42	1,612.51	1,624.92	1,321.16	1,334.77	18,791.23
1960	1,168.41	1,192.71	1,245.58	1,472.17	1,611.38	2,159.27	2,251.61	2,314.19	1,669.56	1,689.59	1,370.96	1,386.56	19,531.99
1961	1,209.31	1,238.41	1,291.21	1,529.24	1,672.54	2,249.70	2,339.40	2,402.96	1,726.61	1,754.26	1,420.76	1,438.35	20.272.75

[1] Based on the average monthly increase in water pumped to the city from 1941 to 1948, see Table 11.

[2] 1948 figures are actual amounts pumped according to city records except for June and July which are adjusted to correct for abnormal water use caused by unusual weather conditions. The amount pumped during June has been reduced and a corresponding amount added to the July use.

than large bodies of water. Comparisons reported by Rowher (9) indicate that a factor of 0.92 applied to land-pan evaporation will give the most probable rate of evaporation from a large surface of water. On this basis, the evaporation from Lake Waco for the assumed period of deficient flow will be about 30 inches.

Comparison of the capacity and area curves for the lake (figures 7 and 8) shows that half the capacity lies above elevation 427, and the area at elevation 427 is about 2,200 acres. Thus the average area exposed during drawdown will be 2,200 acres and evaporation from the lake during the period of deficient stream flow will amount to 5,500 acre-feet.

6. Rainfall for the period of deficient stream flow, August 1939 to March 1940, amounted to 13.5 inches at the Waco gage according to Weather Bureau records. It has been assumed that this amount will fall on Lake Waco during the period of analysis, adding 2,420 acre-feet of water to the available supply.

7. A number of minor factors which tend to compensate are omitted because they cannot readily be computed and the accuracy of the analysis would not be increased by their inclusion. These are:

(a) The gain in water resulting from sediment compaction during the period of analysis. Some water will be released from the sediment as it is exposed and compacted but the volume will be small.

(b) Bank storage will yield an unknown quantity of water which should likewise be small.

(c) Some losses will occur through the dam and outlet works. The amount lost might easily equal the gain from sediment compaction and bank storage sources.

(d) The small amount of sediment which would be deposited in the lake during the period of analysis has been disregarded.

Results of Analysis

Based on the above assumptions, analyses of the reservoir performance at various future dates were made. The results are presented in the following table:

Table 13 - Predicted effect of sedimentation on operation of Lake Waco during a critical drought period.

	Predicted period of deficient flow	
	Aug. 1959 to March 1960	Aug. 1960 to March 1961
	Acre-feet 1/	Acre-feet 1/
Storage capacity at spillway	+ 13,965	+ 13,276
Inflow during period	+ 2,454	+ 2,454
Rainfall on lake's surface	+ 2,420	+ 2,420
Water pumped to city	- 11,725	- 12,170
Evaporation from lake surface	- 5,500	- 5,500
Unavailable storage (ponded)	- 667	- 697
Net volume remaining at end of period	+ 937	- 217

1/ Figures preceded by a plus represent volumes on hand or becoming available during period. Figures preceded by a minus represent volumes removed or unavailable during period.

Table 13 shows that if the predicted minimum inflow should start in August, 1959 the reservoir would have 937 acre-feet of usable water remaining at the end of the period, or enough to meet normal demands for about two weeks. If it should occur one year later the lake's storage capacity would be 217 acre-feet too small to meet the city's needs.

The period covered, from August to March, includes only one month of relatively high water use (see table 11). In 1924 a low flow period of nearly as great deficiency started in July, another month of high water consumption. The next period of deficient flow might readily start in July also, in which case practically all the water would be used from the lake during a drought occurring in 1959-60. Furthermore, evaporation losses are especially large in dry years when low inflow would occur, so the estimated loss from evaporation based on average rates is conservative. Therefore, it is concluded that provision to overcome a serious potential lack of water should be made by 1959 at the latest. Since engineering site studies and construction of storage facilities would require several years time, such work should be started in 1956 or 1957.

POSSIBLE REMEDIAL MEASURES

It seems obvious that most of the ordinary means of maintaining or increasing the capacity of the present Lake Waco would have little effect. Since the reservoir has already lost nearly 50 percent of its original capacity and probably would fail to supply the water requirements of the city, if a drought equal to the maximum should occur as early as 1960, any increase in its capacity would have to be accomplished within the next few years.

Possible solutions of the water supply problem fall into three categories: (1) measures to preserve the remaining capacity of Lake Waco and extend its useful life; (2) development of larger storage facilities on the Bosque River; and (3) additional water supply from sources other than the Bosque River.

Maintenance of the Capacity of Lake Waco

Several methods of reducing rates of sedimentation, thus prolonging the life of a reservoir basin, may be considered. The most common methods are listed below.

Sediment Detention Basins. Any detention basins designed to impound sediment before it reaches the main basin of Lake Waco probably would have to be located upstream from the main reservoir on one or both of the main tributary streams, the North or South Bosque. Considering the topography of the valley and the volume of incoming sediment, relatively large structures would be required to impound any appreciable volume of sediment. Lake Waco itself has a disproportionately small capacity in relation to drainage area and subsidiary basins would have a much more unfavorable ratio. It is believed that any such structures would be impractical considering their cost and short life.

Vegetative Screens. Although sedimentation in the basins of some reservoirs has been retarded by vegetative growth around their headwaters, this procedure appears to be ill-suited to the conditions of Lake Waco. Certain grasses, willows or shrubs could be established in the headwaters areas of the North and South Bosque arms, but the capacities of those segments of the reservoir are already more than 75 percent depleted. Therefore, any additional deposition caused by vegetative screens in those areas would be temporary.

Sluicing. The possibilities for sluicing any appreciable quantity of sediment through the Lake Waco dam are almost negligible. Although the dam was designed and built with large gates at low level for the purpose of by-passing some sediment, attempts to operate these gates have not been successful. On one or two occasions when they were opened, great difficulty was experienced in closing them before a large proportion of lake water had been drained. Also, the broad flat basin of the lake is unfavorable to sluicing operations. Even if the sluice gates could be

operated effectively, most of the water in the reservoir would have to be drained in order to remove any significant quantity of sediment. This procedure is not feasible in Lake Waco because the reservoir has practically no excess capacity.

Dredging. Continuous dredging of sediment from Lake Waco would require constant operation of at least a 12-inch pipeline dredge. In order to maintain existing capacity about 1,000 acre-feet of sediment would need to be removed annually. From experience in other dredging operations, such as that at White Rock Lake at Dallas, it has been found that construction and operation of a 12-inch pipeline dredge would cost about $200,000 annually. Aside from this high cost the problem of disposal of the sediment would be extremely difficult. Only limited quantities could be disposed around the shore line, and the bulk of the discharge then must be released below the dam. This quantity of sediment continually discharged into the river channel below the dam would cause high turbidity in the lower Bosque River channel and even in the Brazos River below the junction.

Erosion Control in the Drainage Area. The average rate of sediment output per square mile in the Bosque River drainage area has ranged from about 1.0 to 0.7 acre-feet per square mile annually. The progress of erosion-control treatment, land-use changes and other factors, as explained in foregoing sections, has been sufficient to cause a decline of more than 35 percent in the rate of sediment production since about 1935. This factor is believed to be very promising for the Bosque River drainage area, especially if accelerated programs of erosion control and water-flow retardation such as those proposed in the recent U.S.D.A.-SCS Flood Control Reports are developed (2, 3). Lake Waco, however, is in such an advanced stage of sedimentation that the long-time results of soil conservation and erosion control measures will not have an appreciable effect before the useful life of the reservoir is terminated. If another water-supply reservoir is built in the lower Bosque River basin this would be a factor of primary importance.

Development of Additional Water Storage before 1960.

In considering the development of additional water supply for Waco three primary considerations appear: (1) development of additional capacity in Lake Waco; (2) the construction of additional impounded storage above or below the present reservoir; (3) the development of other sources.

Raising Lake Waco Dam. The present Lake Waco dam probably could not be raised substantially because of the relatively flat topography of the valley terrace adjacent to the north end of the dam.

Development of New Reservoir Storage Upstream. Detailed surveys have not been made of all possible sites upstream from Lake Waco. Some possibilities for substantial storage, however, have been observed. At least

two possible sites for reservoirs exist in the North Bosque River valley above and below Valley Mills. At least one of these sites has been investigated by the Corps of Engineers. This site is approximately 15 valley miles above Lake Waco but detailed data on cost, capacity and problems of construction are not available. If other solutions to the Waco water supply problem are not considered practical, some upstream sites should be investigated.

Development of New Storage Below Lake Waco. Surveys have been made and a new multipurpose reservoir proposed by the Corps of Engineers at a site about one-fourth mile below Lake Waco dam. The proposed structure would extend between high bluffs and would impound a large reservoir which would completely submerge the present Lake Waco. Preliminary data indicate that a dam in this locality would impound a reservoir having an area of nearly 19,000 acres, a conservation pool capacity of 170,000 acre-feet and a total capacity of 658,000 acre-feet. If the conservation pool should be used for the city of Waco water supply, it would provide ample water storage for nearly 200 years. From the sedimentation survey data on Lake Waco it is predicted that the quantity of sediment transported into the proposed reservoir basin would be about 1,000 acre-feet annually. It is estimated that about 90 to 95 percent of the sediment would be deposited and 10 percent carried over the spillway. This assumption is reasonable since the present Lake Waco now bypasses over its dam 29 percent of the sediment carried into it. The proposed reservoir would have in its permanent pool approximately five times the original capacity of Lake Waco. Then at the present rate of sediment contribution about 900 acre-feet of storage would be lost annually. Such a reservoir would have a much more favorable ratio of original capacity to drainage area. In addition to water supply it would provide protection from floods in the Bosque River valley below the dam and in a segment of the Brazos River valley.

Development of other water sources. Two sources of water outside the Bosque River drainage area offer some possibilities at least for emergency use as water supply. Both have been used before as indicated in foregoing sections of this report. One source is the Brazos River which was used as the principal water supply for Waco for some years. Its disadvantages were a high content of dissolved salts and unreliability of flow during dry seasons. Some improvement in both respects may result from the operation of large new reservoirs recently built on the Brazos River upstream.

The other source is ground water, which also provided the main municipal water supply for a period of years. Four deep wells which furnished the supply before construction of Lake Waco were pumped sufficiently to reduce the water level seriously. The Trinity and Paluxy sands are a well known ground-water resource in the Waco area and many private wells, some for industrial plants, still pump water from these aquifers. It is believed that heavy pumping for city water supply would seriously deplete the water reserves in these formations.

SUMMARY

The principal conclusions of this investigation are as follows:

1. Three detailed surveys of sedimentation in the reservoir have been made. The first survey, made in 1935, showed an original capacity when the dam was built (1930) of 39,378 acre-feet and an area of 2,801 acres. In 1936 the second survey showed that 5.41 percent of the capacity had been replaced by sediment in one year. This was a year of exceptionally high runoff and was not typical of the long-time average sedimentation rate. The 1947 survey showed that 44.07 percent of the original capacity had been replaced by sediment during the life of the reservoir, 1930-1947, at an average rate of 2.49 percent annually. The annual rate of capacity loss has decreased during the life of the reservoir from 2.93 percent (1930-1935) to 2.06 percent (1936-1947). Studies of turbidity of water passing the dam in conjunction with measurements of reservoir deposits show that 71 percent of the sediment transported to the reservoir is deposited and 29 percent passes the dam.

2. The high rate of capacity loss is due to two principal factors: (1) the small original capacity of the reservoir as compared to area of drainage (23.64 acre-feet per square mile); (2) a relatively high rate of sediment contribution from the drainage area.

3. The reservoir survey and studies of turbidity in water passing the dam indicate that the average annual quantity of sediment carried into the reservoir is 1,138 acre-feet. Since the rate of sediment output is declining, predictions of future average annual total sediment load are based on a 1,000-acre-foot average annual contribution as shown by these studies. The average rate of sediment contribution from the drainage area has declined from 1.0 to 0.7 acre-foot annually during the life of the reservoir. This decline of more than 35 percent in rate of sediment contribution to the reservoir is due to the installation of conservation farming methods on more than 10 percent of the drainage area and substantial improvements in land use.

4. As a result of studies of population growth and increase in municipal water use in comparison with rates of capacity loss in the reservoir, predictions have been made of dates at which the reservoir would fail to supply sufficient water during a critical period. It is predicted that if a period of deficient stream flow, similar to those which occurred in 1924-1925 and 1939-1940, should occur as early as 1960, the reservoir capacity would be insufficient to supply the water demand. The hazard of possible water deficiency will become greater if new water supplies are not constructed by 1960. This study does not consider the problems of water filtration and distribution.

5. The best possibilities for increasing the available water supply have been considered. All of these possibilities need further

study before final development. Some deep well development could supply additional water. Emergency use of Brazos River water might be considered. The proposed Corps of Engineers reservoir immediately below the present Lake Waco dam is considered to be the best long-time solution of the water supply problem for the growing city of Waco. Other reservoir sites upstream from Lake Waco might be considered.

LITERATURE CITED

1. Adkins, W. S., Geology and Mineral Resources of McLennan County, Univ. of Texas Bull. No. 2340, Oct. 1923.

2. Bosque River Watershed - Program for Runoff and Waterflow Retardation and Soil Erosion Prevention, U. S. Department of Agriculture (Unpublished), 1947.

3. Brazos River Watershed, Texas, Survey Report, (including the Bosque River) - Program for Runoff and Waterflow Retardation and Soil Erosion Prevention. House Doc. No. 396, 82nd Congress, 2nd Session, March 1952.

4. Eakin, Henry M., Silting of Reservoirs, USDA Tech. Bull. No. 524 (Revised by Carl B. Brown), August 1939, pp. 73-78.

5. Geib, H. V., and Goddard, L. P., Reconnaissance Erosion Survey of the Brazos River Watershed, USDA Misc. Publ. No. 186, 47 pp., Feb. 1934.

6. Hill, H. O., and others Investigations in Erosion Control and Reclamation of Eroded Land at the Blackland Conservation Experiment Station, Temple, Texas, 1931-1941, Table 9, p. 58, U. S. Dept. of Agriculture Tech. Bull. 859, Jan. 1944.

7. Report on the Water Distribution of Waco, Texas; two reports dated 1929 and 1944. The Pitometer Company, Engineers, New York City.

8. Report on Survey of the Brazos River and Tributaries, Texas, Volume 2, Department of the Army, Corps of Engineers, Galveston District Office, August 1947.

9. Rowher, Carl, Evaporation from Different Types of Pans, Amer. Soc. of Civ. Engineers Trans. 99, pp. 673-703, 1934.

10. U. S. Department of Commerce, Weather Bureau Climatological Data, Texas, Annual Summary - 1930-1948.

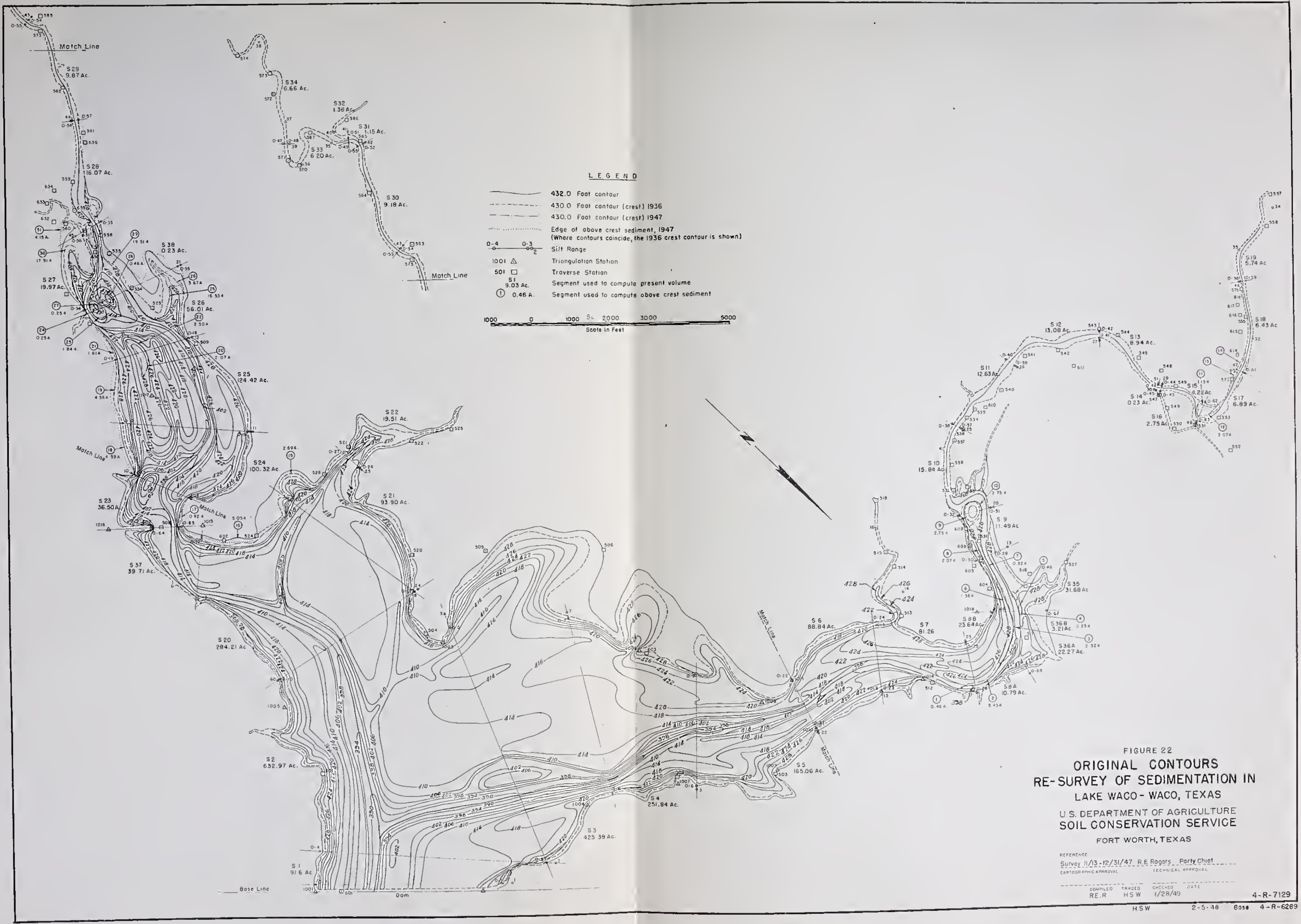


FIGURE 22

ORIGINAL CONTOURS
RE-SURVEY OF SEDIMENTATION IN
LAKE WACO - WACO, TEXAS

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

REFERENCE
Survey 11/13-12/31/47 R.E Rogers Party Chief
CARTOGRAPHIC APPROVAL TECHNICAL APPROVAL

COMPILED	TRACED	CHECKED	DATE
RE.R	HSW	1/28/49	

4-R-7129

H.S.W 2-5-48 Base 4-R-6289

AGR-SCS-FT WORTH,TEX. AUGUST,1952

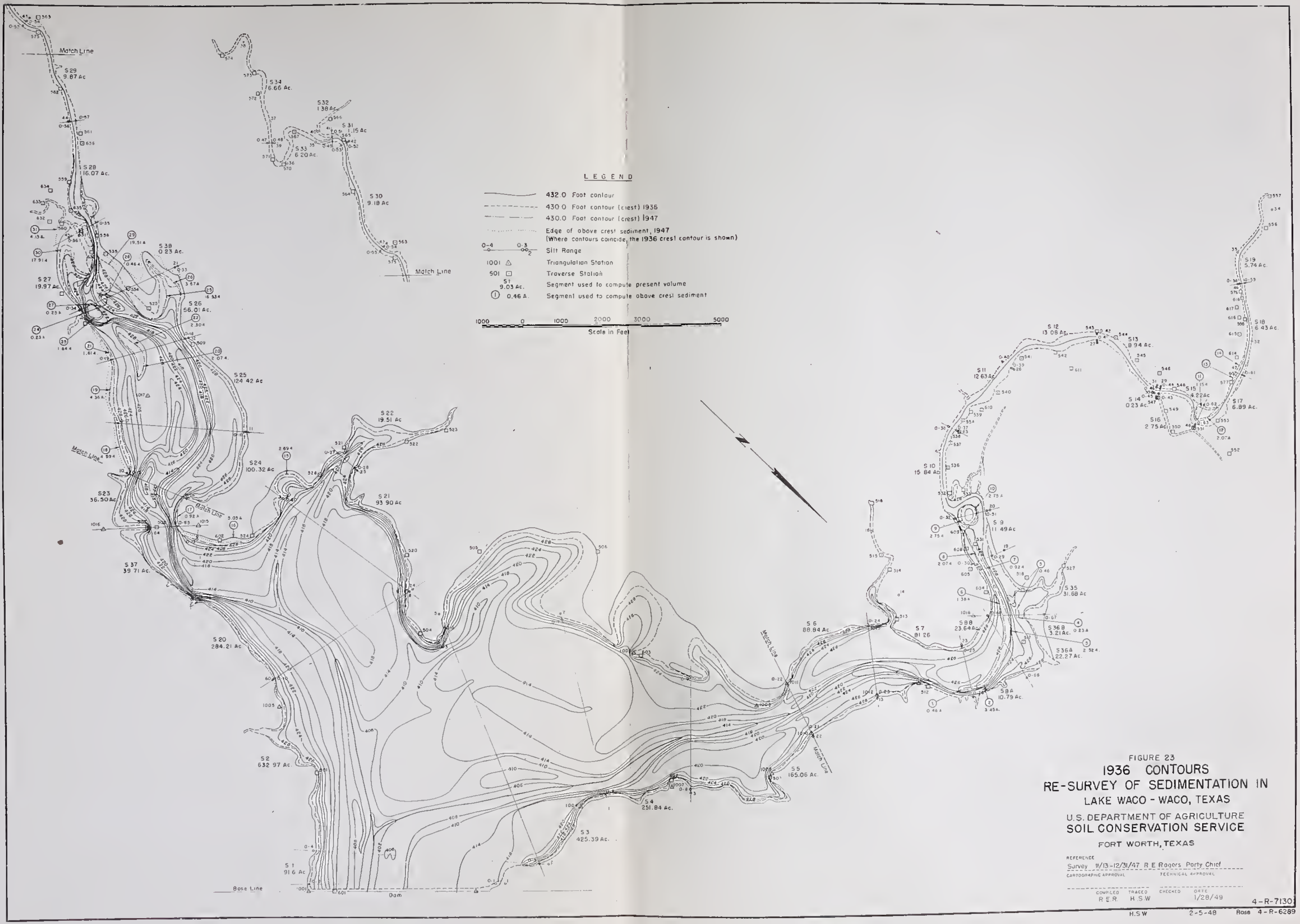

LEGEND
432.0 Foot contour
430 0 Foot contour (crest) 1936
430.0 Foot contour (crest) 1947
Edge of above crest sediment, 1947
(Where contours coincide, the 1936 crest contour is shown)
0-4 0-3 2 Silt Range
1001 △ Triangulation Station
501 ⊡ Traverse Station
S1 9.03 Ac. Segment used to compute present volume
① 0.46 A. Segment used to compute above crest sediment
1000 0 1000 2000 3000 5000
Scale in Feet
Match Line
Base Line
Dam
S 1 91.6 Ac
S 2 632 97 Ac.
S 3 425.39 Ac.
S 4 251.84 Ac.
S 5 165.06 Ac.
S 6 88.84 Ac.
S 7 81 26
S 20 284.21 Ac
S 25 124 42 Ac

FIGURE 23

1936 CONTOURS
RE-SURVEY OF SEDIMENTATION IN
LAKE WACO - WACO, TEXAS

U.S. DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE
FORT WORTH, TEXAS

REFERENCE
Survey 11/13-12/31/47 R E Rogers Party Chief
CARTOGRAPHIC APPROVAL
TECHNICAL APPROVAL

COMPILED	TRACED	CHECKED	DATE
R.E.R.	H.S.W		1/28/49

4-R-7130

H.S.W 2-5-48 Base 4-R-6289

AGR-SCS-FT WORTH,TEX AUGUST,1952

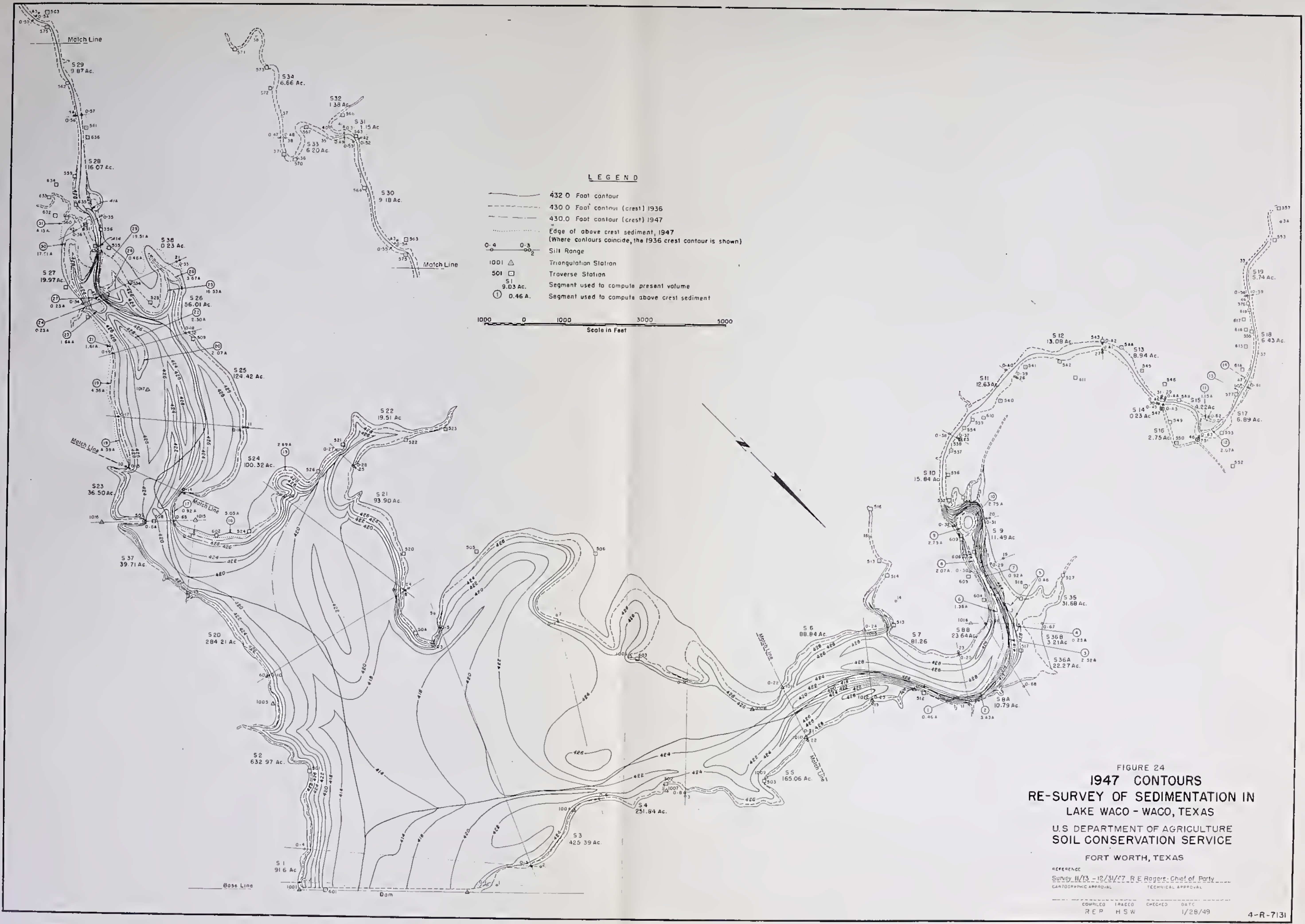


FIGURE 24

1947 CONTOURS
RE-SURVEY OF SEDIMENTATION IN
LAKE WACO - WACO, TEXAS

U.S DEPARTMENT OF AGRICULTURE
SOIL CONSERVATION SERVICE

FORT WORTH, TEXAS

REFERENCE	Survey 11/13 - 12/31/47 R.E. Rogers - Chief of Party
CARTOGRAPHIC APPROVAL	
TECHNICAL APPROVAL	

COMPILED	TRACED	CHECKED	DATE
R E P	H S W		1/28/49

4-R-7131

AGR-SCS-FT WORTH,TEX AUGUST,1952

H S W 2-5-48 Base 4-R-6289